SUPPLEMENTAL LIGHTING
for
GREENHOUSE CROPS

Ir. J.J. Spaargaren

along with

Hortilux Schréder B.V.
and
P.L. Light Systems, Inc.

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FOREWORD

Since the previous edition of this book (Application of growlight in greenhouses, 1985), several advances have been made in the field of supplemental lighting of greenhouse crops.

The design of supplemental lighting installations can be optimized using sophisticated computer models. New luminaires are available with ever increasing efficacies (efficiency of converting electric energy into useful light – usually expressed in lumen per watt). High-Pressure Sodium (HPS) lamps are widely used for their highest conversion efficiency (approximately 30%). Further increases in conversion efficiencies are expected. *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* are continuing to contribute towards this goal.

Research in plant physiology uncovered many crop responses to supplemental lighting. It is becoming clear that not only light intensity should be taken into consideration but also light sum, lighting period, and corresponding daylength. Particularly the daylength may have a significant impact on growth and development, as will be discussed in this book. Integrated light sums are now used to indicate threshold values below which problems can occur with flower initiation, development, growth rate, and branching.

The basis for plant growth is the increase in dry matter. The building blocks for dry matter increase are supplied by photosynthesis. In addition to light, carbon dioxide, and water, chlorophyll content and the appropriate temperature determine the rate of photosynthesis. The optimum rate of photosynthesis is only attainable when none of these growth factors are limiting. For example, a high root temperature during rose production considerably increases the consumption of sugars through respiration. As a result, the net rate of whole-plant photosynthesis may decline even to the point of an overall loss of biomass despite the use of supplemental lighting to increase plant growth rates.

Plant nutrition also has a major impact on plant growth. Without proper nutrition, the necessary building blocks, such as enzymes, will not be available. Therefore, plant nutritional aspects will also be addressed in this book.

Contents

The book starts with a **Summary** and a table presenting a brief overview of the production methods used for supplemental lighting of various greenhouse crops in The Netherlands. On page 6 is explained how to adjust minimum light levels of supplemental lighting to the natural light sums in other countries.
Using supplemental lighting is more than installing luminaires. Supplemental lighting interacts with many other production aspects and, thus, with the overall management of a greenhouse operation. It is important that a grower uses the correct lighting strategies. *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* have several tools to provide recommendations (**Chapters 1 and 2**).
Subsequent chapters describe the physics and plant physiology behind supplemental lighting. **Chapter 3** describes the basic physical principles of light as electromagnetic radiation. The effects of the light spectrum on plant growth and development are summarized in **figure 3.29**.
Chapter 4 discusses some of the plant physiology behind growth and development.
Chapter 5 focuses on the units of light an their conversions.
In **Chapter 6**, recommendations for supplemental lighting strategies are presented. These recommendations include light intensity, light sum, daylength, etc. The light intensity provided by the installed supplemental lighting system can be compared with the desired light levels for *e.g.* foliage plants, flowering pot plants, and cut flowers. The information provided for pot plants also discusses minimum light levels for the end user (inside the consumer's living room) because this information is important for maintaining satisfactory plant quality. For cut flowers, threshold values are presented below which plant quality problems can be expected.
At the **end** of **Chapter 6**, supplemental lighting recommendations for greenhouse vegetable production are presented.
Chapters 7 through 11 discuss the technical aspects of supplemental lighting installations.
Chapter 7 discusses the various light sources.
Chapter 8 describes the construction of luminaires, in **8a** for Europe and in **8b** for North America, and **Chapter 9** presents the luminaires produced by *Hortilux Schréder B.V.* (in **9a**) and *P.L. Light Systems, Inc.* (in **9b**).
Chapter 10 discusses the process by which *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* design and quote supplemental lighting installations.
Chapter 11 describes the electrical installation.
Finally, a **Reference list** and an **Index** are included to help a reader find information quickly.

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I am especially indebted to Tjeerd who gave me valuable stimulating advice. He thoroughly reviewed the first six chapters.

This **second edition** of the book in English would not have been accomplished without the excellent translation work, improvements and additions for the world market of:

- Dr. Theo J. Blom, Greenhouse Floriculture, Department of Plant Agriculture, University of Guelph, Vineland Station, Ontario, Canada,
- Dr. Arend-Jan Both, Assistant Extension Specialist, Rutgers, The State University of New Jersey, Bioresource Engineering, Department of Plant Science, U.S.A.,
- Drs. Willem van Winden, Research Station for Floriculture and Glasshouse Vegetables in Naaldwijk, The Netherlands.

Special thanks go to Arend-Jan and Theo with whom I have exchanged countless e-mails.
Finally, I want to thank publishers*, researchers and companies for the use of information and graphics.

Ir. Jaap Spaargaren, Aalsmeer, The Netherlands, August, 2001.

* ***The following publishers kindly permitted to reprint figures from their publications.***
Agricultural Institute of Canada, *figure 6.15, from Demers et al.,1991, in Canadian Journal of Plant Science.*
American Society for Horticultural Science, *figure 4.13, from Heins et al., 1986, in the Journal of American Society of Horticultural Science, figure 6.13 from Blain et al., 1987, in HortScience, figures 6.17 and 6.19 from Boivin et al., 1987, in HortScience.*
American Society of Plant Biologists (formerly American Society of Plant Physiologists), *figure 3.16, from Zscheille et al, 1942 in Plant Physiology.*
Elsevier Publishers, *figures 6.14 and 6.16, from Van Uffelen and Heuvelink, in Groenten en Fruit.*
Elsevier Science, *figure 6.3, from Bruggink, 1987, in Scientia Horticulturae, figures 3.21 and 3.22, from McCree, 1972, in Agricultural Meteorology.*
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Headley Brothers/The Invicta Press, *figures 6.18, 6.20, 6.21, 6.22,6.23, 6.26, 6.27, from McAvoy, Janes (1991) and Cockshull et al. , 1992 and 1995, in The Journal of Horticultural Science and Biotechnology.*
International Society for Horticultural Science (ISHS), *figure 4.10, from Morisot, 1996, figure 4.14, from Faust and Heins, 1997, figure 3.18, from Schurer in Acta Horticulturae.*
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Sinauer Associates, Inc., Publishers, *figure 3.24, from Vierstra and Quail, 1983, in Taiz and Zeiger, 1998, Plant Physiology.*
Dr. T.C. Vogelmann*, University of Wyoming, figure 3.19.*
Wageningen Press, Publishers*, figures 3.13, 4.6 and 4.7 from Gijzen, in Greenhouse Climate Control.*
Complete references are to be found in the back of the book.

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SUMMARY

Supplemental lighting of greenhouse crops is a complex issue involving many aspects of plant physiology and business management. The added costs of operating supplemental lighting systems should be off set by an increase in revenue for added plant production and/or quality. Increased knowledge gained from plant physiology research allows us to precisely predict plant responses to lighting strategies.

When providing recommendations for supplemental lighting strategies, it is important to note the range of light conditions that elicit plant responses. These ranges are usually expressed as light sums (light intensity multiplied by duration) and they usually have a linear relationship with the dry matter production of plants (0.60-0.65 g/mol). This linear relationship allows for a fairly accurate prediction of the effects of supplemental lighting on plant production. Both for photosynthesis and other crop responses there are optimum values for daylength (lighting period), light intensity, and light sum. These light quantities expressed in *micromole* ($\mu mol\ m^{-2}\ s^{-1}$) *and mol* $m^{-2}\ d^{-1}$, respectively, have shown good correlation to photosynthesis and production. Units such as *lux / footcandle, or luxhour / footcandlehour* are less fitting for correlation with plant growth.

The efficiency with which the light energy is used for photosynthesis *(the so-called Light Use Efficiency or LUE)* varies, depending on environment conditions, plant density *(expressed as Leaf Area Index or LAI)*, crop mass, the type of plant leaves (sun leaves or shade leaves), and plant age. These factors should be optimally adjusted, leading to the greatest possible difference between production (photosynthesis) and consumption of sugars (respiration). The net photosynthesis is zero under low light conditions *(= light compensation point)* and levels off over a given light level (saturation). These points are important for cultivation and keeping quality.

Daylength may also play an important role in the LUE. Considering an equal light sum, it is sometimes recommended to maintain a lower light intensity during a longer period of time compared to a higher intensity during a shorter period (*e.g.* rose production). For other crops, the reverse is recommended. Furthermore, daylength may affect stem formation (*e.g.* rose), dry matter distribution (freesia), and the biological rhythm of plants. For example, if the daylength becomes too long for certain rose cultivars the stomates no longer close, which has a negative effect on keeping quality.

Daylength can also affect flower initiation. For short-day plants, the use of supplemental lighting during the short-day phase is limited (*e.g.* 11-12 hours for chrysanthemums). On the other hand, many daylength neutral and long-day plants are able to handle a 16 to 24 hour photoperiod.

To elicit daylength effects, low light intensities are sufficient (1-2 $\mu mol\ m^{-2}\ s^{-1}$). These low intensities are often provided by incandescent lamps. We call this technique *photoperiodic lighting*. Lighting to promote photosynthesis requires much higher intensities.

Changes in daylength are sensed by plants with the help of *phytochrome*. This pigment exhibits activity peaks in red and far red light. The light of HPS lamps contains little far-red light. For this reason, these lamps cannot be used for long-day plants such as carnations and gypsophila, while they can be used for chrysanthemum (short-day plant).

The *phytochrome* pigment also influences plant elongation. When the red/far-red ratio declines, elongation of the main shoot increases. This occurs under incandescent light, but the reverse occurs under the light of high-pressure sodium lamps. HPS lamps have a much higher red/far red ratio. Elongation is further inhibited by blue/violet light. Additional pigments are involved *(e.g. cryptochrome)*. Note that blue and violet light are a very small component of the light of high-pressure sodium lamps (6%). Red light promotes the breaking of axillary buds, which may lead to production increase, for example in rose.

The light spectrum of lamps greatly influences their effectiveness and applications. To promote photosynthesis, high-pressure sodium lamps are the most frequently used because they are the most efficient in converting electric energy into useful light. Due to their limited light spectrum, however, they are not suitable for grading produce. Grading requires lamp types with a high color rendering index**.** Thirty-five percent of the radiant energy produced by high-pressure sodium lamps is in the waveband between 2,800 and 10,000 nm. Most of this radiant energy is absorbed by the leaves, resulting in a temperature rise of the irradiated plant parts.

The daily light sum requirement for horticultural crops ranges from low (5-10 mol $m^{-2}\ d^{-1}$) for African violet to very high (30-50 mol $m^{-2}\ d^{-1}$) for rose and chrysanthemum. In Northern countries daily light sums in greenhouses vary during the course of a year from 1 to 35 mol $m^{-2}\ d^{-1}$. Thus, it is obvious that supplemental lighting can be useful for many crops during most parts of the year.

A standard plant production curve (biomass production plotted versus time) is often more or less S-shaped. The middle part is (almost) linear. Young leaves of plants with low light saturation levels (shade plants) are not capable of adapting themselves to higher light levels as sun plants are. For shade plants, the maximum light intensity is reached sooner than for sun plants. Finally, it is not recommended to operate the supplemental lighting system based on daily light sum when the light levels are close to the minimum required levels. Further limitation will definitely lead to loss of growth.

Table I: ***Recommendations for supplemental lighting of some horticultural crops (52^{0}N.L.).***

	Minimum Intensity *PPF* [1] *(µmol m^{-2} s^{-1})*	**Daylength** *(hours)*	**Comments**
Adiantum spp.	35	16	raising/production
Aechmea	50	16	raising/production
Ageratum	30-65	16-20	raising/sowing
Aglaonema	30	15-18	production
Alstroemeria	60	11-14	production
Antirrhinum	60-100	20	sowing/raising
Argyranthemum	70	8-11	cutting production
Aster ericoides	32	20/11-13.5	production long-day/short-day
Begonia Elatior	40-50	16-22	cutting production
	35	9/18-22	short-day/long-day
Begonia tuberhybrida	65	14-20	raising
Bouvardia	54	11	production short-day, min. light sum 3.7-4.1 mol m^{-2} d^{-1}
Calathea spp.	30	15-18	production
Calceolaria	30-40	16-18	production
	4.6	16-18	production/photoperiodic lighting with fluorescent light
Campanula isophylla	40-90	12	cutting production, vegetative growth
	30-40	16	production
Chrysanthemum	50	20/11	propagation/production, minimum light sum 4.6-6.8 mol m^{-2} d^{-1}
	1.5-2	16/	photoperiodic lighting, production/
	1.5-2	20	stock plants
Cissus rhombifolia 'Ellen Danica'	45	16	production
Codiaeum variegatum	45-50	18	production
Cordyline fruticosa	30-40	16	production
Cucumber	50-100	24	propagation/raising
	150	18-20	cultivation
Cyclamen	35-50	18	seed production/raising/prod.
Dianthus caryophyllus (Carnation)	100	12	propagation
	1	24	photoperiodic lighting/production
Dieffenbachia	35-60	15-18	production, cultivar dependent
Dracaena spp.	40	16	production
Eggplant (Aubergine)	50-100	20	propagation/raising
	150	20	cultivation
Epipremnum pinnatum	30	14	production
Euphorbia pulcherrima	35/60	10/20	production/mother plants, short-, long-day
Eustoma (Lisianthus)	75-100	20-24	production, minimum light sum 9 mol m^{-2} d^{-1}
Exacum	50-75	18	production
Fatshedera	45	16	raising/production
Ficus benjamina	30-45	16-18	propagation/production
Ficus elastica	60	20	production
Freesia	35-50	14-16	production/ corm development daylength to 20 h
Fuchsia	35	11	propagation
Gazania	50-60	16	raising/production
Gerbera	50-100	16-20	production
Gladiolus	1-4	16	photoperiodic lighting for long day effect, minimum light sum 13 mol m^{-2} d^{-1}
Guzmania	50	16	propagation/production
Hedera helix	45	16	production
Hibiscus rosa-sinensis	60-70	20	production
Howeia forsteriana	50	16	production
Hyacinth[2]	23	12	forcing with fluorescent lamps
Hydrangea	30-45	16-20	forcing
Impatiens New Guinea	70	16-20	propagation/production

N.B. Minimum intensities and hours of supplemental lighting are given for conditions in The Netherlands.
For more northern or southern latitudes these intensities should be adjusted according to natural light sums (Moe, 1993).
Please, turn to page 6 for explanations.
Dr. Jim Faust at Clemson University provides "light maps" that show the average daily light integral in mol m^{-2} d^{-1} throughout the United States in dfferent months of the year. These light maps can be downloaded from http://virtual.clemson.edu/groups/hort/faculty/faust/maps.htm.

Table I: ***Recommendations for supplemental lighting of some horticultural crops (52⁰N.L.).***

(continued)

	Minimum Intensity *PPF [1] (μmol m⁻² s⁻¹)*	**Daylength** *(hours)*	**Comments**
Impatiens	60-100	24/	propagation long-day/
		13	production short-day
Iris (Dutch)	35-50	20	production, minimum light sum 5 mol m⁻² d⁻¹
Kalanchoe	30-100	10/16-22	production short-day and long-day phase
	40	16-20	propagation long-day
Lettuce [3]	150	13-18	regular year-round production
Lilium (Asian)	40-60	20-24	production, minimum light sum 5.3 mol m⁻² d⁻¹
Lilium longiflorum	30-40	16-24	production, minimum light sum 3.7 mol m⁻² d⁻¹
Lilium L/A hybrids	40-60	20-24	production, minimum light sum 5.3 mol m⁻² d⁻¹
Lilium Oriental	50	16	production, minimum light sum 4.1 mol m⁻² d⁻¹
Maranta spp.	30	15-18	production
Narcissus [2]	23	12	forcing with fluorescent lamps
Nephrolepis exaltata	35-50	16/20	sowing/sprouting, raising, production
Nidularium	50	16	propagation/production
Pelargonium zonale	70	18	propagation/production
Pelargonium peltatum	70	16	propagation/production
Pelargonium grandiflorum	35-70	16-18	production, long-day after cold period
Pelargonium (seed)	70	16-20	sowing/raising/production
Petunia	65/	24/	sowing/production,
	30-65	12/16	short-day branching/long-day flowering
Phalaenopsis	40-160/	20/	propagation long-day/
	40-60	10	production short-day
Playcerium bifurcatum	30-50	16	propagation
Pteris spp.	30-50	16	propagation
Radermachera sinica	60	20	production
Rosa (pot rose)	135/75-100	24/20	rooting/production, cultivar dependent min. light sum 8 mol⁻² d⁻¹
Rosa (cut flower)	100	16/24	production, cultivar dependent minimum light sum 12-13 mol m⁻² d⁻¹
Saintpaulia (African violet)	40-50	16	production, minimum light sum 4 mol m⁻² d⁻¹
Schefflera arboricola	30	18	raising/production
Sinningia	35-40	20-24	raising/production
Spathiphyllum	30	16	raising/production
Streptocarpus	35-40	20-24	raising/production
Sweet pepper	50-100	16-24	propagation/raising
	150	20	production
Syngonium podophyllum	60	24	production
Tomato	50-100	16-18	propagation/raising
	175	16-18	production, more flower abortion below 3.1 mol m⁻² d⁻¹
Trachelium	45-55	18-24	production
	1.75	18-24	photoperiodic lighting, after August 1, cyclic 10-15 min per half hour
Tulip[2]	23	12	forcing with fluorescent lamps
Vriesea	50	16	propagation/production
Yucca elephantipes	75-100	20-24	raising and bud outgrowth
Zinnia	75-100	24/	raising/
		10-12	production, short-day accelerates flowering

[1]) PPF = Photosynthetic Photon Flux, light intensity (μmol m⁻² s⁻¹)
[2]) during forcing
[3]) Below 12-13 mol m⁻² d⁻¹ growing periods increase very fast. At about 2 mol m⁻² d⁻¹ growth rate is zero, depending on circumstances.

Adjusting minimum levels of lighting in Table I

The aim of lighting is to supply at least a minimum of light in the darkest months of the year. The starting point is the light sum per day or daily light integral. Supplementing natural light sums with light of HPS lamps minimum light sums per day can be obtained in winter. For this, minimum light intensities and number of lighting hours are mentioned in Table I. In many cases more light would be better. As the data in this book apply to Holland, for other parts of the world figures should be adjusted. In comparison with Naaldwijk (52^0 N.L.) during most of the year monthly light sums become higher going to the south (Table III), and lower going to the north, except in summer.

Table II. ***Decrease of light per degree of latitude*** *from Naaldwijk (52^0 N.L.) to Oslo (60^0 N.L.).*
Represented are natural average light intensities (calculated over 24 hours!) in greenhouses with 60% transmission. Source: Moe. 1993.

	Decrease per degree of latitude: light intensity, watt m^{-2} PAR	light intensity, *μmol m^{-2} s^{-1}	light sum, mol m^{-2} d^{-1}
October	0.79	3.63	0.31
November	0.50	2.30	0.20
December	0.58	2.67	0.23
January	0.76	3.50	0.30
February	2.11	9.71	0.84

* 1 μmol m^{-2} s^{-1} average sunlight = 0.2174 watt m^{-2} PAR

North of Naaldwijk

According to Moe (1993) between Naaldwijk (52^0 N.L.) and Oslo (60^0 N.L.) for every degree increase of latitude the natural average light intensity **(calculated over 24 hours)** in greenhouses with 60% transmission decreases accordingly Table II. The accessory daily light sums should be compensated by lighting. In Table I minimum intensities of supplemental lighting should be adjusted, in proportion to the number of hours lamps are switched on.

For example, lighting for 12 hours in stead of 24, light intensity in December should be doubled from 2.69 to 5.38 μmol m^{-2} s^{-1} . This is per degree of latitude.

So, with regard to Naaldwijk (52^0 N.L.) at Oslo (60^0 N.L.) minimum light intensity in December should be raised with 8 x 2.69 = 21.5 μmol m^{-2} s^{-1} when lighted for 24 hours, and 8 x 5.38 = 43.0 μmol m^{-2} s^{-1} when lighted for 12 hours.

This could be applied to Alstroemeria for example (page 4). The recommended minimum light level for supplemental lighting of this crop is 60 μmol m^{-2} s^{-1} at Naaldwijk, this PPF should be raised with 43 μmol m^{-2} s^{-1} to 103 at Oslo when lighted for 12 hours.

South of Naaldwijk (See also Note on page 4.)

In Ontario average light sum is 100% higher in December than in Naaldwijk. There is a difference of 2 mol m^{-2} d^{-1}. This is often the extra light sum given by supplemental lighting to plants with no need of much light. For example this light sum can be obtained by lighting for 16 hours with a PPF of 35 μmol m^{-2} s^{-1}.

This is precisely how ferns like Adiantum, Platycerium and Pteris are lighted in Holland. But don't conclude in this case that in Ontario no supplemental light is needed for these plants. A daily light sum of 4.8 mol m^{-2} d^{-1} is just a minimum. Extra supplemental light could be very beneficial for plant growth and development, quality and growth rate. Light exceeding minimum daily light sums, is linearly related to the increase in dry weight of plants (§ 4.2).

As pointed out in Section 6 plants could be distinguished for the light requirement in different categories. Shade plants having a low light requirement, reach their optimum or maximum growth between 5 and 10 mol m^{-2} per day, African Violet (Saintpaulia) for example at 8-10 mol m^{-2} d^{-1}. Plants with an average light requirement of 10-20 mol m^{-2} d^{-1}, high with 20-30 mol m^{-2} d^{-1} or very high with 30-50 mol m^{-2} d^{-1}, the more light the better in winter. It's up to the grower to decide when the luxury level is reached with supplemental lighting.

However, too high light intensities could be harmful for shade plants. These levels for some foliage plants (Table 6.6) and flowering potplants (Table 6.8) are reached between 200 and 300 μmol m^{-2} s^{-1} in general. This depends on cultivars and season for example. In February/March plants coming out of the winter are more sensible than in autumn. These levels can be compared with average natural light intensities in Southern Ontario, as to be seen in Table IV. From October to February natural light intensities for shade plants could be raised with 50-100 μmol m^{-2} s^{-1} without harm. Sun plants can stand much higher levels. Crop photosynthesis of rose and tomato is only saturated at intensities over 1,000-1,500 μmol m^{-2} s^{-1}.

Table III. Average daily light sums in greenhouses
in mol m^{-2} d^{-1} with 60% transmission at Naaldwijk (52^0 N.L.), Niagara (S. Ontario, $43^0 15'$ N.L.) and Ithaca ($42^0 25'$ N.L.).

	Naaldwijk	Niagara	Ithaca
January	3.0	5.2	5.8
February	6.1	9.6	9.4
March	10.6	15.2	14.3
April	17.5	19.4	17.0
May	22.3	25.0	21.8
June	24.5	27.0	25.4
July	23.0	25.8	24.5
August	19.5	21.8	21.7
September	13.3	16.6	16.0
October	7.7	10.2	10.9
November	3.6	6.0	5.9
December	2.3	4.8	4.6

Table IV. Average daily light intensities in greenhouses
in μmol m^{-2} s^{-1} with 60% transmission at Naaldwijk (52^0 N.L.), Niagara (S. Ontario, $43^0 15'$ N.L.) and Ithaca ($42^0 25'$ N.L.).

	Naaldwijk	Niagara	Ithaca
January	103	154	174
February	178	254	254
March	256	353	342
April	356	400	360
May	401	472	421
June	413	484	467
July	399	471	460
August	375	433	438
September	297	365	361
October	207	258	279
November	118	172	171
December	84	150	144

1 *History of Hortilux Schréder B.V. and P.L. Light Systems, Inc.*

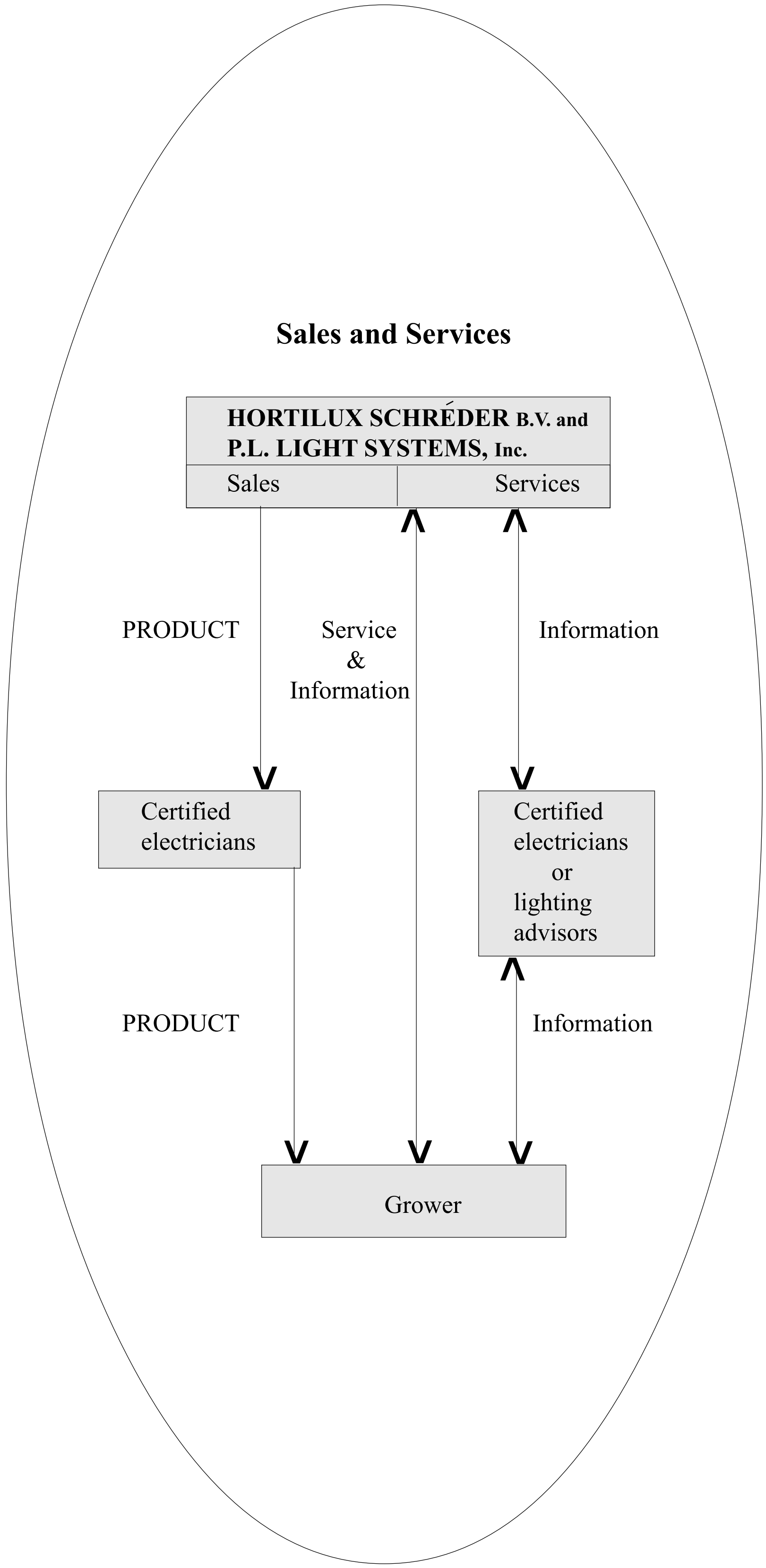
Many crops can only be grown profitably during the winter months with the help of supplemental lighting. The advantages are better quality, higher yield, and improved growth rate. Supplemental lighting is increasingly used during the darker months when sunlight or sun light hours are limited. This is particularly true for areas at a higher latitude (> 40 N.L or S.L).

For many years *Hortilux Schréder B.V.* participated in the growth of the industry. In 1975, Mr. J. Poot started selling fixtures manufactured by Constructions Electriques Schréder S.A. in Liège, Belgium. This manufacturer is still regarded globally as market leader in the field of street lighting systems. The former Poot Lichtenergie B.V. has, under the leadership of Mr. T.C. van den Dool (owner of the company), grown into *Hortilux Schréder B.V.*. The Schréder family maintains a financial interest in *Hortilux Schréder B.V.*.

Since 1981, the North and South American markets have been serviced under the name *P.L. Light Systems, Inc*. The company resides in Beamsville, Ontario, Canada. The reflectors are still exported from The Netherlands, while all electrical components such as ballasts, capacitors, and lamps are provided through North American markets. This is done to avoid problems with differences in voltage and frequency (usually 220 volt at 60 Hz in most European countries and 120 volt and 50 Hz in North America).

Hortilux Schréder B.V. and *P.L. Light Systems, Inc.* conduct their own lighting and manufacturing research. The companies run sophisticated laboratories, where new fixture and reflector are developed and tested. For example, our reflectors are manufactured with moulds developed specifically for *Hortilux Schréder B.V. and P.L. Light Systems, Inc.*.

Hortilux Schréder B.V. and P.L. Light Systems, Inc. don't provide installation of its luminaires. This is done worldwide by certified electricians. Like our growers, our electricians can count on expert advice during the installation process.



2 *Company philosophy*

Hortilux Schréder B.V. and P.L. Light Systems, Inc. sell light luminaires. This seems a simple matter, but it is not. The challenge is to find the ideal combination of fixture, reflector, distribution pattern, and mounting height. The computer can help design commercial systems, but for successful projects it is important to work closely with growers and electricians. Therefore, *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* offer a unique set of tools to optimize supplemental lighting installations.

The success of supplemental lighting depends on other environment parameter such as temperature, relative humidity (RH), carbon dioxide concentration (CO_2), crop nutrition, and plant architecture. All these parameters need to be optimized before supplemental lighting can be of benefit to the plants.
Hortilux Schréder B.V. and P.L. Light Systems, Inc are able to predict the maximum efficiency of a supplemental lighting installation at the lowest possible costs. This analysis is presented in a so-called lighting plan. For example, such a plan present what light level, light distribution, and light uniformity are provided by a particular lighting design.

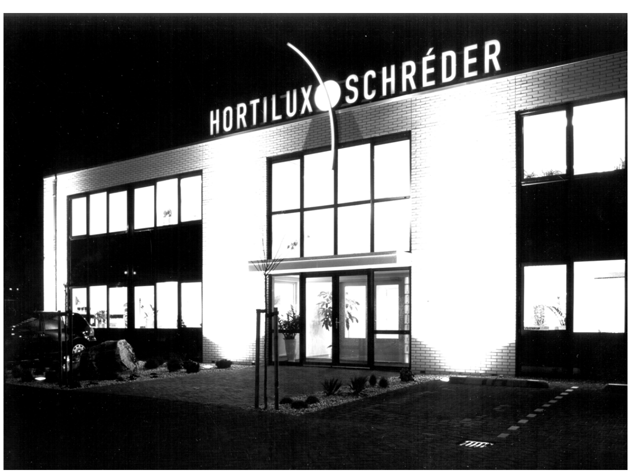
Hortilux Schréder B.V. and P.L. Light Systems, Inc have many years of experience advising growers on all the ins and outs of the optimum combination of fixtures, reflectors, distribution patterns and mounting height. We always try to design in such a way that optimal results are obtained with the fewest possible fixtures. A sophisticated computer program, which was specifically designed for *Hortilux Schréder B.V. and P.L. Light Systems, Inc.*, is used to calculate the light levels and uniformity for any possible design.
Hortilux Schréder B.V. and P.L. Light Systems, Inc. guarantee their lighting plans. In addition, we offer a fast and efficient service and work together with the certified electricians. If desired, *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* offer a service and maintenance plan for all your lighting equipment. Besides excellent quality, *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* also guarantee reasonable prices. Just ask us for a quote.

Hortilux Schréder B.V. and P.L. Light Systems, Inc. are working on a bright future for our industry. Research is conducted to increase the performance of our fixtures, design dimmable fixtures, and provide lighting systems with adjustable light spectra. In addition, new developments are expected with respect to fixture and ballast design, indoor and outdoor lighting systems, and lighting of plant growth chambers. Before any of these new developments are taken into full-scale production, they are carefully tested both in our own laboratory and in the field.

Recently, *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* announced a breakthrough in supplemental lighting for greenhouse vegetable production. This breakthrough will allow for a tremendous growth in the coming years.

HORTILUX SCHRÉDER
Supplemental Lighting

P.L. LIGHT SYSTEMS
Member of HORTILUX SCHRÉDER GROUP



Advantages of working with *Hortilux Schréder* B.V. and *P.L. Light Systems,* Inc.

Marketing

1. Our fixtures are sold through a certified dealer network.
2. Our staff directly communicates with the end users (growers).
3. We guarantee our lighting plans.
4. We provide a custom-made lighting plan for each grower.
5. We closely follow the latest horticultural and plant physiological developments.
6. We have an excellent research and development department.
7. We maintain close cooperation with our suppliers.
8. We live by an innovative attitude.

Technical aspects

1. Our customer support staff has a lighting technical background.
2. We provide a custom-made lighting plan.
3. We design for the highest light uniformity.
4. We guarantee optimal irradiation of your crop.
5. We guarantee the highest light conversion efficiency.
6. We provide expert technical lighting recommendations.
7. We operate sophisticated measuring equipment.
8. We maintain a high level of customer service.
9. Our delivery times are short
10. We offer competitive pricing.

Organization

1. We maintain a well-oiled organization.
2. We purposely maintain short communication lines within the company.
3. Our family owned company works from a single location.
4. Our staff is friendly and responsive.
5. We focus on customer needs.
6. We continually implement new developments.
7. We are very quality driven.
8. We have many years of experience with supplemental lighting for the greenhouse industry.

3 *The physics of light*

Introduction

The sun provides us with heat and food through the ability of plants to perform photosynthesis. On earth, plants and animals have been able to survive in part due to the fact that gases like ozone (O_3), oxygen (O_2) and N_2O in the atmosphere absorb most of the harmful ultraviolet radiation, specifically UV-C and part of UV-B (with wavelengths smaller than 300 nm) (Salby, 1995).

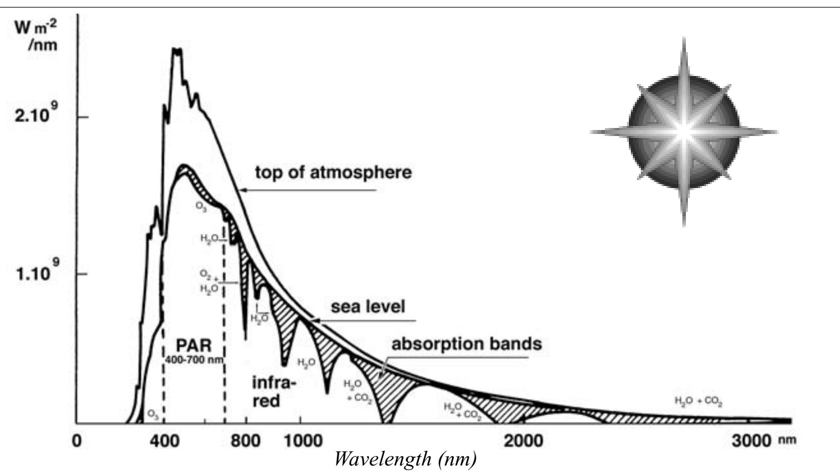
Sun radiation from 300 to 3,000 nm is largely transmitted through the atmosphere. At the earth's surface on average 45% of the solar or global radiation energy is received as PAR light. This part of visible radiation is used for photosynthesis of plants ranges between 400 and 700 nm (Figure 3.1). Only a small percentage of the total energy of global radiation, about 5%, is fixed in sugars by a leaf (Taiz, 1998), the rest is converted into heat radiation.

Once conditions became suitable to sustain plant life, the percentage of oxygen in the atmosphere increased while the carbon dioxide concentration declined. As a result of the position and rotation of the earth, we experience seasons with changing day-length and weather conditions (*e.g.* light intensity and temperature). Living organisms have adapted to these conditions. Through research, we know a lot more about the effects of the different colors of light (spectrum) on plant growth and development. In addition, it has become possible to mimic sunlight by using different sets of lamps.

Hortilux Schréder B.V. designs lighting systems, both for supplemental lighting to increase plant growth and for photoperiodic lighting to manipulate the day/night rhythm of short-day and long-day plants. This allows us to bring flowers to bloom any time of the year, independent of their natural flowering season. But light is not the only growth factor. Other growth factors need to be considered as well. For example, by supplying extra carbon dioxide, the efficiency of the supplemental lighting can be significantly increased. A carbon dioxide concentration increase from 360 to 700 ppm results in an average production efficiency increase of 19%. The successful use of supplemental lighting requires insight into growth and energy management of plants. For example, it is preferred that the energy required to operate a supplemental lighting systems is used to boost photosynthesis, but not necessarily to increase transpiration. In this book, the effects of light on plant growth will be discussed in greater detail.

Plants use a different part of the light spectrum for photosynthesis than humans. Therefore, common light units such as *footcandles (ft-c), lux (lx)*, and to a lesser extent *watt (W)*, are less appropriate.

Figure 3.1. ***Spectral energy distribution of solar radiation*** *at the top of the atmosphere and at sea level. The atmosphere absorbs almost all harmfull radiation from 100 to 300 nm by N_2O, O_2 and O_3. Between 300 and 3000 nm there are absorption bands of O_3, O_2, H_2O and CO_2. At sea level on average 45% of solar radiation falls in the Photosynthetically Active Radiation (PAR) waveband of 400-700 nm, (see also Figure 4.16).*
Adapted from N. Robinson, 1966 and Salby, 1995.



3.1 Light, radiation and spectrum

Light

Light is electromagnetic radiation with wave and particle (photons) characteristics. It can be represented as a flow of photons with certain wavelengths, moving forward in a certain direction at a speed of approximately 300,000 km per second (in vacuum). Important light characteristics include energy, wavelength, and frequency.

Wave characteristics of light

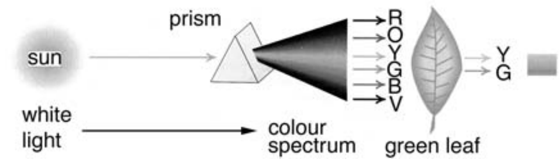
Wavelength

The wavelength is the distance between adjacent crests of a wave. The unit of measurement is often nanometer (1 nm = $1 \cdot 10^{-9}$ m). Visible radiation has wavelengths between 380 and 770 nm. In literature, the ranges identifying the different colors of light and visible light (especially the upper limit) often vary. For colours this is usually because of rounding. For example, 455 nm may become 450 or 460 nm. Wavelengths of electromagnetic radiation vary from $1 \cdot 10^{-14}$ m to 100 km. Radio, television, and telephone use wavelengths between 10 cm and 10 km. Waves have electric and magnetic components, hence the name electromagnetic radiation (Figure 3.3).

Frequency (Hz, ν)

The frequency is a measure of the number of wave crests that pass a given point during a specific time interval. Frequency is usually expressed as the number of waves or vibrations per second (s^{-1} or *Hertz*). Green light, with an average wavelength of 550 nm, falls in the middle of the visible light spectrum, and has a frequency of about $6 \cdot 10^{14}$ vibrations per second. Frequencies of electromagnetic radiation start at about $1 \cdot 10^{4}$ s^{-1} and end with the harmful cosmic radiation at $1 \cdot 10^{24}$ s^{-1}. Visible light is only a small portion of the entire radiation spectrum. As the frequency increases, the energy contained in the radiation increases. The reverse is true for wavelength.

Figure 3.2. ***Spectrum of sunlight.***
Spectrum means array of color bands, resulting from separation of the different colors of light.
White sunlight contains all colors of the spectrum, as can be shown when sunlight is separated by a prism.
Leaves are green because they partly transmit and reflect green light with adjacent wavelengths while they strongly absorb red and blue light.
Source: Galston, 1997.



Spectrum

Most physical phenomena can be adequately explained with the theory of electromagnetic radiation. This theory also describes the separation of white light in a continuous set of colors (rainbow) as it passes through a prism (Figures 3.2 and 3.5).

Light spectrum

Visible radiation generally ranges between 380 and about 770 nm, enclosed by ultraviolet and infrared. The color violet starts at 380 nm, and as the wavelength increases, the colors change into indigo, blue, green, yellow orange, red, to 700 nm. Physiologists use far-red light that starts at 700 nm and ends at 770 nm. However, in literature the classification in the range between 700 and 800 nm is not uniform. Sometimes far-red is skipped or ends between 750-800 nm. The light spectrum is only a small part of the entire electromagnetic radiation spectrum. A large part of the solar radiation is invisible (Figure 3.5). Lamps used for supplemental lighting can also emit a lot of invisible radiation.

Figure 3.3. ***Wave characteristics of (light) radiation with electrical and magnetic components.***

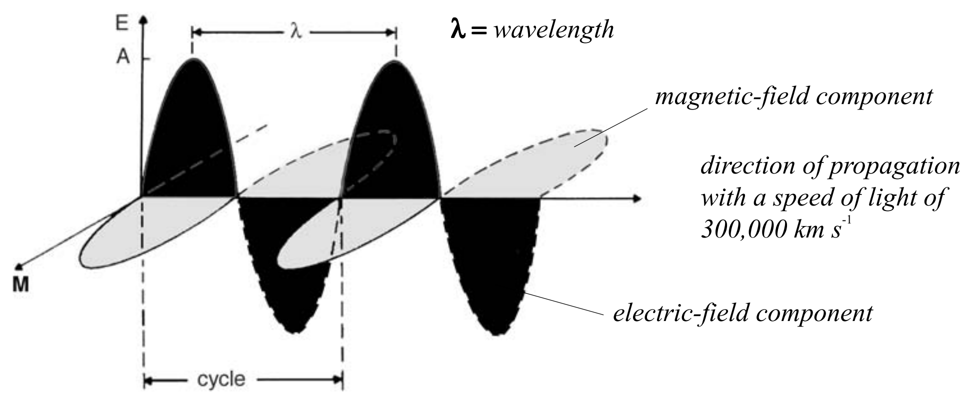


Figure 3.4. ***Kipp-pyranometer (solarimeter).***
This radiometer, CM 11, measures global solar radiation in the waveband of 305-2,800 nm (50% points), or 295-3,200 nm (10% points), or 280-4,500 nm (1% point).
Source: Kipp & Zonen B.V., 2001.

Invisible radiation
Important are:
- ultraviolet and
- infrared

Ultraviolet
Ultraviolet radiation has wavelengths between 100 and 380 nm. UV-A and UV–B have a distinct effect on plant growth. For more details, see Section 3.3. Harmful wavelengths shorter than 286 nm don't penetrate to the earth's surface (Robinson, 1966) but can be generated by special lamps, for example to kill bacteria. Between 300 and 286 nm only a very small amount of UV radiation reaches the surface, depending on *e.g.* the height. Between these limits at the top of the atmosphere UV-B energy is 0.61% of the solar constant (energy) (Robinson, 1966). After passing the atmosphere there is no much left at sea level, less than 0.01% (ISO/TC180/SC, 1987). Ultraviolet with wavelengths lower than 380 nm accounts for 7.29% of the solar constant, at sea level roughly speaking about 5% of global radiation (Salisbury,1992).

Infrared
Infrared (IR) radiation is divided into near, middle and far-infrared radiation as NIR between 770 and 2,500 nm, MIR between 2,500 and 30,000 nm, and FIR between 30,000 and 1000,000 nm, (Schneider, 1996). Infrared radiation is often called heat radiation. Like far-red, the classification of infrared is in literature not uniform. Measured at sea level, wavelengths longer than 720 nm account for about 50% of global radiation (ISO/TC180/SC, 1987).

Human visual response
The sensitivity of our eyes is highest in the region around 555 nm and lowest at 400 and 700 nm. However, outside these borders our eyes are still able to distinguish colors. Therefore, the limits of *"visible radiation"* lie between 380 and about 770 nm.

Figure 3.5. ***Visible and (part of) the invisible electromagnetic radiation.***

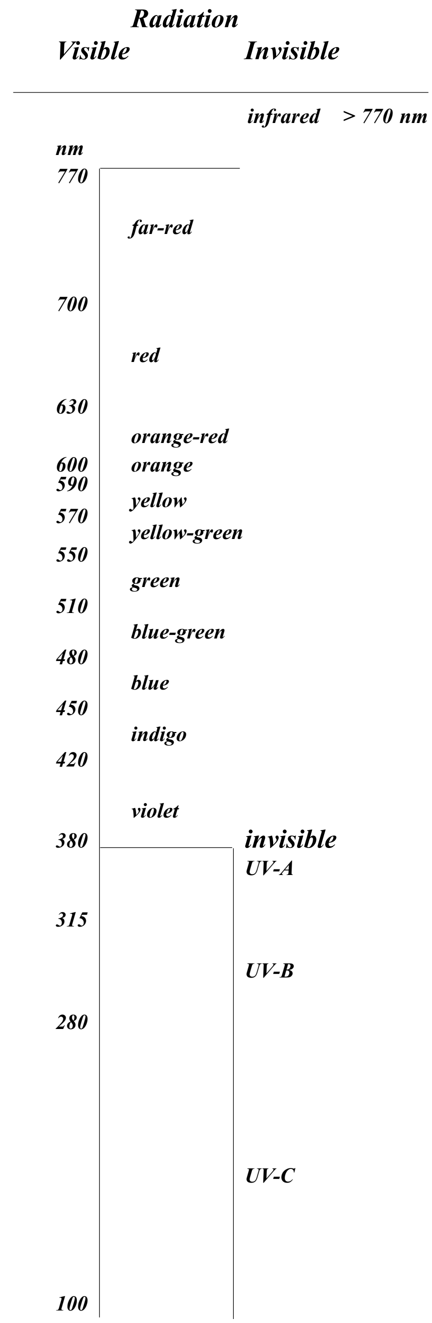


Figure 3.6. ***Spectral response of the human eye.***
Source: Downs, 1975.

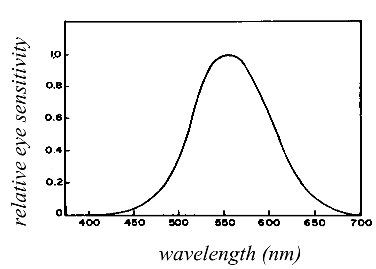


Figure 3.7. ***Spectral energy distribution of an incandescent lamp***

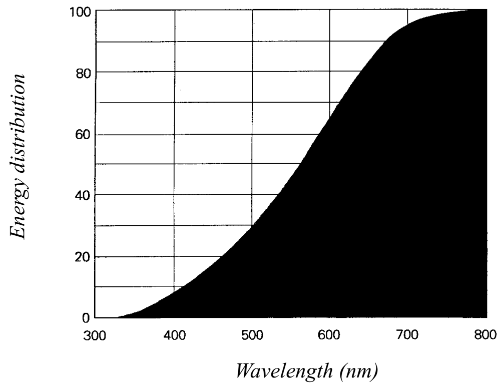
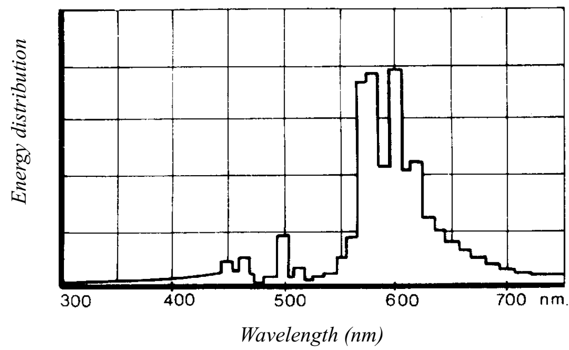


Figure 3.8. ***Spectral energy distribution of the High-Pressure Sodium Lamp SON-T***



Global radiation

At the upper boundary of the atmosphere the total sun irradiance is 1,360 W m^{-2} (the solar constant), which includes ultraviolet and infrared wavelengths. The solar radiation reaching the earth's surface is on average 900 W m^{-2} (Salisbury, 1992). Wavelengths between 300 and 3,000 nm account for most of the energy 98,96%, between 280-2,800 nm 98,89% (ISO/TC180/SC, 1987).This so-called (global) short-wave radiation can be measured with a pyranometer in the units of watt per m^2 (Figure 3.4). The Kipp pyranometer is often used in Holland and in North America the Eppley Precision Spectral Pyranometer (PSP). Considered from 1% point they measure in the band of 280 and 2,800 nm. This means that the transmission of radiation through the two domes of glass (4 mm K5), protecting the sensor, is less than 1%.

Global radiation can be divided in direct and diffuse radiation. In Dutch winters the ratio between diffuse and global radiation is more than 0.7, and the middle of May 0.44. The more clouds the more diffuse radiation (Velds, 1992).

Black body radiator

Our sun is termed a so-called black body radiator. This seems strange for a light source that emits perfectly white light. The term black body radiator indicates that the surface of the sun is very hot. The color of the emitted light then only depends on the surface temperature. The higher the surface temperature, the more (light) energy is emitted. Compare for example when an object is heated, it first becomes red-hot and finally white-hot.

Figure 3.9. ***Light color index of different Philips lamps expressed in kelvin (K)***

colour	*K*	*lamps*
	7,000 K	
		TL-D/965
daylight white	6,000 K	TL-D/950
	5,000 K	
neutral white		HPI TL-D 58W/33 (cool white)
	4,000 K	TL-D 58W/840 (cool white)
	3,300 K	
	3,000 K	
warm white		incandescent lamp PLE 20W
	2,000 K	SON-T Plus
	1,000 K	

Temperature of the sun

The surface of the sun is very hot, about 5,800-6,000 kelvin (K = 273 + °C), depending on the layer (Salisbury (1992), Salby (1995). The solar spectrum outside the earth's atmosphere (Figure 3.1) matches closely the spectrum of a black body at 6,000 K. The sun emits radiation with wavelengths between about 100 and 1,000,000 nm (Robinson, 1966).

Continuous spectrum

The sun emits a continuous spectrum. The individual colors merge in a continuous spectrum. Incandescent lamps have the same characteristic (Figure 3.7). The temperature of the filament is around 3,000 K. As a result, most energy is released in the red, far-red and infrared, and the light is less white compared to sunlight.

Line spectrum

Fluorescent (FL) lamps do not produce light by heating a filament. FL light is called 'cold light' and these lamps are more efficient in converting electricity into light compared to incandescent lamps. The spectrum is often very specific. Low-pressure sodium lamps produce only yellow light in a narrow waveband. When light colors or narrow wavebands are separated, a spectrum is called a line spectrum. Line spectra are frequently produced by gas discharge lamps, such as high-pressure sodium, metal halide, and high-pressure mercury lamps.

Light color of lamps

Light has different effects on plants. It promotes growth, but it can also be used to promote special effects. In that case, light is used to create a specific atmosphere in offices, homes, and stores.

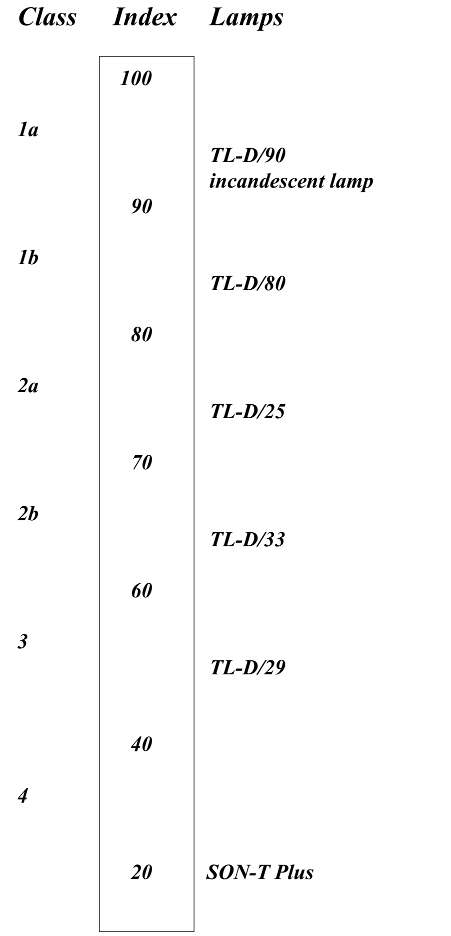
Comparing the color of light with the emittance temperature of sunlight
About 40 minutes after sunrise, the emittance color temperature is around 3,000 K (warm white). Around noon, the emittance color temperature has increased to slightly more than 5,000 K (neutral white). However, the radiation from an overcast sky may be more intense than that from direct sunlight, resulting in the light blue color associated with an emittance color temperature of 8,000 K. These color indications can be used to compare sunlight with the color of light produced by different lamps (Figure 3.9).

Energy distribution of lamp light
Light measurements of different light sources, especially spectral distribution measurements, can be used to compare different light sources. The maximum light or energy level emitted by each light source can be used to indicate the light color. For example, light sources with a emittance color temperature of more than 5,000 K belong to the daylight white group, between 3,300 and 5,000 K to neutral white, and below 3,300 K to warm white (Figure 3.9). Incandescent lamp (2,700 K) and the high-pressure sodium lamp SON-T Plus, (2,000 K) obviously belong to the latter group. Fluorescent lamps emit light with many different colors, while for example mercury iodide lamps HPI (4,400 K) belong to the neutral white group.

Color rendition
Another aspect of light is the so-called color rendition (Figure 3.10). Colors of flowers and clothing often look differently outdoors and indoors. This is caused by the different spectra of the light sources. The colors of objects are the result of the varying degrees of absorption (by pigments in their surfaces) of the various wavelengths of the light falling on them. For example, a pigment or coloring agent is blue if it absorbs all wavelengths, but reflects the blue wavelengths. Black objects absorb all visible radiation, while white objects reflect all colors. If wavelengths are lacking in the light spectrum of a lamp, these obviously cannot be reflected from a surface. For example, when blue wavelengths are missing in light falling on a blue object, the object will not appear as having a natural blue color.

Working and living environment
The importance of color rendition depends on our living and working environment. To properly display flowers and vegetables, either in a retail store or for grading purposes, lamps must be used which emit a full warm white spectrum. But for road lighting, the color rendition is not so important as long as the objects are clearly visible. High-pressure sodium lamps give a limited spectrum with peaks in the yellow orange range (72% of the energy is emitted in the wavelength between 565 and 625 nm). In the same waveband, our eyes are very sensitive. Plants exposed to high-pressure sodium light appear pale in color

Figure 3.10. ***Color rendering index of Philips lamps.***



because only 8% of the energy is emitted in the green waveband.

Color rendering index
Light emitted from lamps is usually characterized by a color rendering index (CRI) represented by a number between 0 and 100. Incandescent lamps have an index of 100. A SON-T Plus lamp has an index of 20 and is therefore not suitable for indoor lighting when color rendition is important. In schools and offices, a CRI of 80-90 is required. Fluorescent lamps are available with many different CRI's. Plant grading requires a high CRI.

Particle characteristics of light *(photon)*
Through radiation, energy (expressed in the unit *joule*) is emitted and transferred, for example from the sun or a lamp to plants. The radiation energy can be described as having wave characteristics and particle characteristics. To explain the interaction between radiation and for example chlorophyll, the wave theory of light is not sufficient. For this reason, a so-called quantum theory was developed, based on the assumption that energy behaves like a flow of particles (photons) or energy packages. Wave characteristics such as frequency and wavelength can be used to describe the energy content of a photon. The energy of each photon (**E**) is proportional to the frequency with which each particle vibrates, or inverse-

ly proportional to its wavelength. Therefore, as the wavelength decreases the energy content increases. Consult the box for some useful formulas.

Relationship photons and photosynthesis

To describe the role of light in the process of photosynthesis, it is best to think of light as a number of particles (photons). The unit of micromole (μmol, which equals $1 \cdot 10^{-6}$ mole) of photons, is often used to describe *Photosynthetically Active Radiation (PAR)* with wavelengths between 400 and 700 nm. As in chemistry, one mole of light contains a fixed amount of photons. Avogadro's number defines this fixed amount: $6.023 \cdot 10^{23}$. Therefore, one mole of light contains Avogadro's number of photons and one micromole contains $6.023 \cdot 10^{17}$ of photons. Independent of its wavelength (color), one PAR photon is capable of activating only one chlorophyll molecule.

For example violet photons (400 nm) can be compared with red photons (700 nm).

Violet light at 400 nm has an energy content of:

300 kJ per mole of photons (mol^{-1}),

while **red light** at 700 nm has an energy content of:

171 kJ per mole of photons (mol^{-1}).

Consequently, violet photons at 400 nm have 1.75 times more energy compared to red photons at 700 nm. However, during photosynthesis red photons are just as effective as violet photons. The extra of energy of the violet photons is lost as heat (Figure 3.11).

Lighting for plant growth

The efficiency of lighting for plant growth depends on light absorption of photons and not necessarily on light intensity (or radiant energy expressed in watt or $J\ s^{-1}$). Per watt received radiation the number of photons increases as the wavelength gets greater.

Figure 3.12: ***LI-250 Light Meter***
using different radiation sensors, such as:

- quantum sensor for PAR (PPF) (μmol s^{-1} m^{-2}),
- photometric sensor for illuminance (lux),
- pyranometer sensor for global radiation (watt m^{-2}).
Source: LI-COR.

The number of photons per watt is at:

- 400 nm: 3.33 μmol s^{-1}
- 700 nm: 5.85 μmol s^{-1}
- on average: 4.60 μmol s^{-1}

(μ= micro = one millionth = $1 \cdot 10^{-6}$)

The number of photons received per second per joule of violet light is only 57% of the number of photons received per joule of red light. A similar ratio is observed in the action spectrum for crop photosynthesis (Figure 3.13).

Measurements

The photon flux can be measured with for example a LI-COR quantum meter (Figure 3.12).

Energy calculation for a mole of quanta or photons according to Salisbury (1992):

$E_\lambda = h \cdot \nu$ for each photon, in which is
h = Planck's constant $6.6255 \cdot 10^{-34}$ J•s per photon
ν = frequency (pronounced as nu)
$\nu = \frac{c}{\lambda}$
c = velocity of light = $3 \cdot 10^{8}$ meter s^{-1}
λ = wavelength (lambda)

E per mole or $E\ mol^{-1} = h \cdot \nu\ mol^{-1}$
1 mole of photons is equal to:
Avogadro's number: $6.023 \cdot 10^{23}$

Energy (**E**) per photon at a certain wavelength, *e.g.* a red photon of 660 nm:

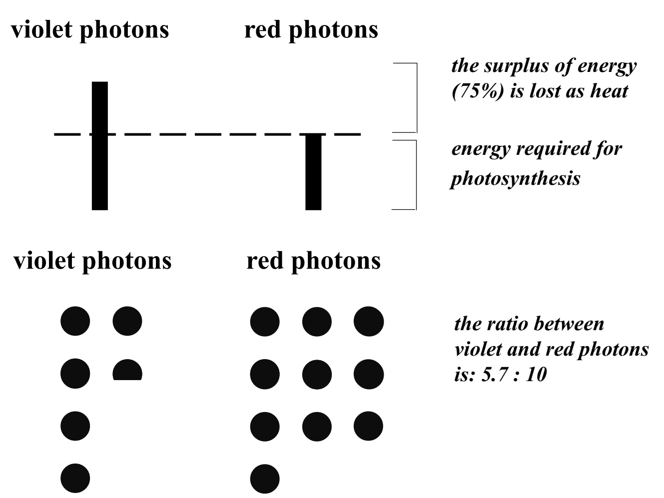
$$E = h \cdot \frac{c}{\lambda}$$

$$E = \frac{(6.6255 \cdot 10^{-34}\ J \cdot s\ photon^{-1} \times 3 \cdot 10^{8}\ meter\ s^{-1})}{660\ nm = 6.6 \cdot 10^{-7}\ m}$$

$E = 3.01 \cdot 10^{-19}$ J per photon of red light of 660 nm.

Energy content per mole =
$3.01 \cdot 10^{-19}$ J $photon^{-1}$ x $6.023 \cdot 10^{23}$ photons mol^{-1} =
181,000 J mol^{-1} = 181 kJ mol^{-1}

Figure 3.11. Top: ***Relative energy content of one mole of violet photons (400 nm) compared with red photons (700 nm).***
For photosynthesis, the energy associated with each photon of red red light is sufficient. The surplus of energy of violet photons is lost as heat.
Bottom: ***Relative number of violet and red photons for the same amount of energy.***

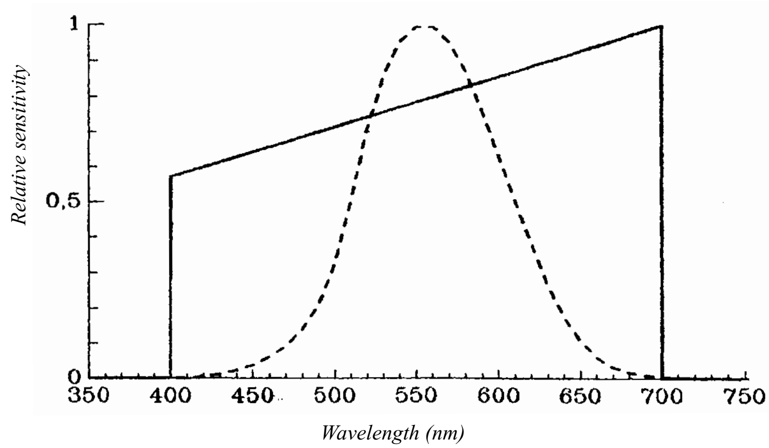


3.2 Plant response and human visual response

***Figure** 3.13. **Relative spectral sensivity of plant and humans to PAR radiation**.*

***Plant sensitivity** related to photosynthesis activity (**solid line**), (CIE, 1993). Virtually all PAR light between 400-700 nm is absorbed at a leaf area index (LAI) of 3 to 5. In fact this curve represents crop photosynthesis activity. Sensitivity curves of chlorophyll and separate leaves are not linear (Figures 3.15-3.23).*

***The sensitivity of the human eye** over the same waveband (**dashed line**).*
Source: J.C.Bakker et al. , 1995.
(Reprinted with permission from Wageningen Press, Publishers.)



Light sensitivity

Light sensitivity is determined by pigments. In humans, these pigments are located in the eyes so that radiation can be sensed (seen) as light with different colors. In plants, pigments are located in chloroplasts, structures, which are actively involved in photosynthesis. Light sensitivity is different for plants and humans (Figure 3.13). Plants are much more sensitive in the blue and red region of the visible light spectrum compared to the green region. In addition, plants are much more sensitive in the red region compared to the blue region. These differences in sensitivity play an important role when we measure light either as visible light (based on the sensitivity of the human eye and usually expressed in *footcandles or lux*) or as *photosynthetically active radiation (PAR)* at 400 – 700 nm. This will be discussed in more detail later. To understand the plant response to light, the absorption and action spectra should be investigated. The plant response corresponds with the action spectrum. This allows for an interpretation of the influence of various wavelengths on photosynthetic activity. For supplemental lighting purposes, the curve in Figure 3.13 is very important. Not only should lamps emit light that promotes photosynthesis, but these lamps should also convert electric energy into useful light efficiently. First, we investigate how much light plants absorb at different wavelengths and subsequently what plants do with it.

Absorption spectrum and action spectrum

These spectra have an important impact on photosynthesis. For photosynthesis, plants use light with wavelengths between 400 and 700 nm (PAR).
On average, 85 to 90% of PAR reaching the leaves is absorbed, the rest is reflected or transmitted (Figure 3.14). Light energy is also taken up by other pigments not involved in photosynthesis, e.g. those active in the protection against ultraviolet radiation (anthocyanins).
Absorption of light by plants can be studied at different levels, which may help to explain the different effects of light more clearly.

Light absorption of:

Dissolved Pigments	-	***Level 1***
Chloroplasts	-	***Level 2***
Single Leaves	-	***Level 3***
Crop	-	***Level 4***

Figure 3.14. ***Optical properties of a bean leaf.***

Shown are the percentages of light absorbed, reflected, and transmitted, as a function of wavelength.
The transmitted and reflected green light in the wave band at 500 to 600 nm gives leaves the green colour.
Note that most of the radiation beyond 700 nm is not absorbed by the leaf.
Source: Smith, 1986. (Reprinted with permission from Kluwer Academic Publishers, Dordrecht.)

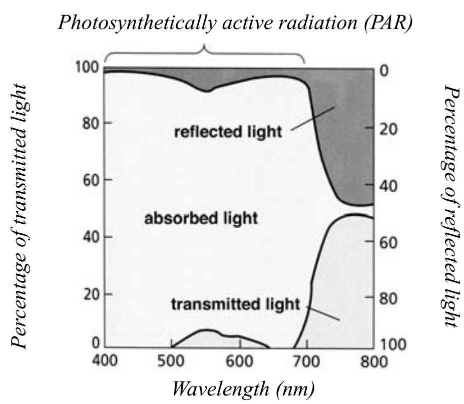


***Figure 3.15.* Level 1**
*Light absorption of chlorophyll **a** (being the most important) and **b**. These pigments are active in photosynthesis. For measurements they are extracted from chloroplasts and dissolved in diethyl ether.*
Source: Zscheile et al., 1941.
(Reprinted with permission from Harvard College Library.)

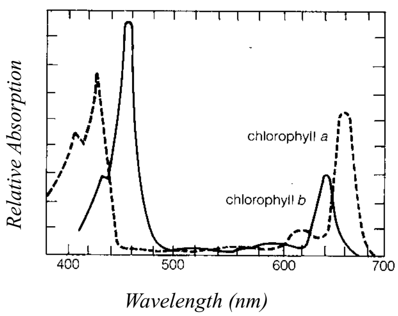


***Figure 3.16.* Level 1**
Light absorption of carotenoids: β-carotene and lutein. They absorb light energy which they pass on to chlorophyll. β-Carotene is dissolved in hexane and lutein in ethanol. In living leaves absorption of the carotenoids shifts from blue into green. Source: Zscheile et al., 1942.
(Reprinted with permission from Am. Soc.Pl. Biol.)

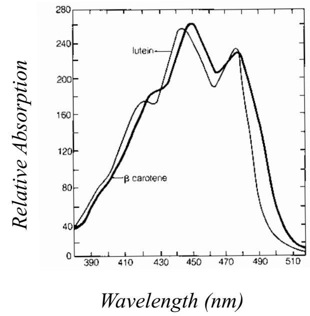
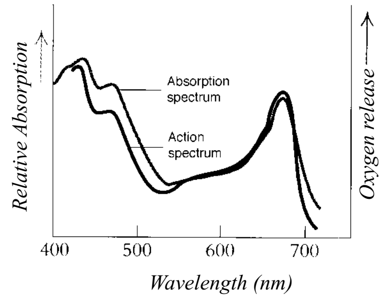


***Figure 3.17.* Level 2**
Light absorption of chloroplasts. The action spectrum, showing the biological effect of light, agrees to a great extent with absorption. The action spectrum is measured by plotting oxygen evolution.
Source: Galston, 1997.



Absorption by pigments: Level 1

This process is based on the absorption by separate pigments that are active in photosynthesis, such as carotenoids (carotene and xanthophyll), and chlorophyll ***a*** and ***b*** (Figures 3.15 and 3.16). These pigments absorb light with certain wavelengths, while transmitting other wavelengths. Each pigment has its own fingerprint, characterized by the wavelengths it absorbs and the degree of absorption. Pigments can be separated from the chloroplasts by dissolving them in special chemical solutions. Once separated, the pigments are tested for absorption. Peak absorption for the chlorophylls occurs in the blue and the red wavelengths. For carotenoids, peak absoprtion occurs in the blue wavelength (450 – 470 nm).

Absorption by chloroplasts: Level 2

If the light absorption of chlorophyll pigments (Figures 3.15 and 3.16) is compared to the absorption of chloroplasts (Figure 3.17) or that of leaves, the pigments appear to be less identifiable. This is caused by the presence of other, non-active pigments, which do absorb light, sometimes overlapping with the photosynthesis pigments. Furthermore, energy transfer takes place among the various pigment systems. Usually, most energy is transferred to the chlorophyll a pigment.

Absorption by leaves: Level 3

Light radiation transmitted in the green area of the spectrum and which consequently penetrates the leaf tissues, is both scattered and reflected. In the process, these photons increasingly have a chance to get absorbed and used for photosynthesis in the parenchyma tissues of the leaf. In the end, half or more of the light penetrated is absorbed and used for photosynthesis. This explains why leaves absorb PAR (between 400 and 700 nm) almost completely (Figure 3.18). There is a small dip in the yellow-green area (around 550 nm). This dip depends on the type of crop, the quantity of chloroplasts (development stage of the leaf) and leaf type (*e.g.*, sun or shade leaf, Figures 3.19 and 4.1).

Absorption by crop canopies: Level 4

Whole crop canopies are able to absorb more light than individual leaves (Figure 3.20). In crop canopies, transmitted and scattered light is absorbed as well as the number of leaf layers increases.

***Figure 3.18.* Level 3**
Light absorption of a Hibiscus leaf.
Source: Schurer, IMAG-DLO.
(Reprinted with permission from ISHS.)

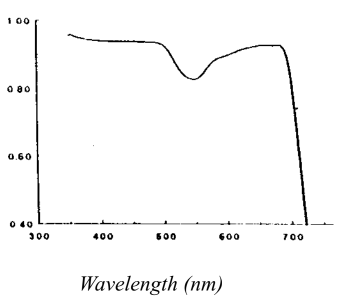


Figure 3.19. *Thick sun leaf with long columnar palisade cells that stand in parallel columns several layers deep. Below layers of spongy mesophyll which also absorb transmitted light. Source: Dr. T.C. Vogelmann.*

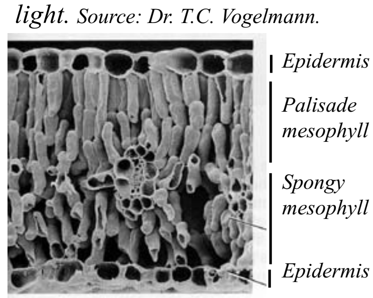
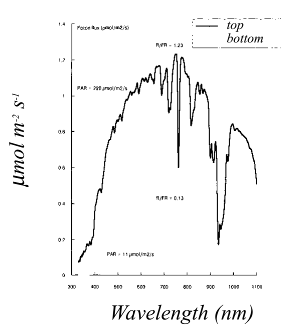


***Figure 3.20.* Level 4**
Light measurements above and in a rose crop canopy (2 Sept. 1991, 14 h).
Source: AB-DLO, 1991.



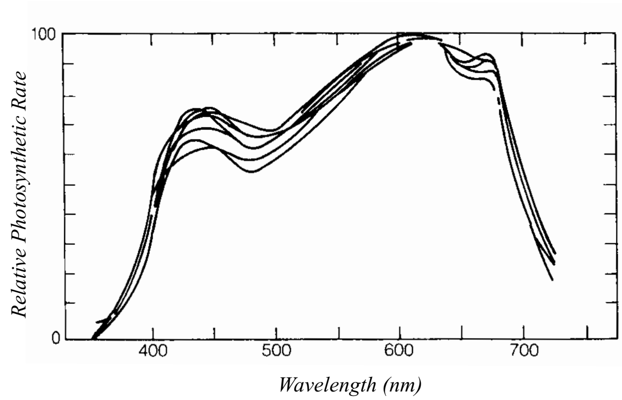


Figure 3.21. ***Action spectra*** *of separate leaves coming from 22 species of crop plants.*
The action spectrum is determined by measuring the photosynthetic rate (CO_2 uptake) at various wavelengths. Measuremens were made at a constant photosynthetic rate with standard conditions of 350 ppm CO_2, 75% RH and 28°C leaf temperature.
As the uptake of CO_2 is divided by absorbed photons per wavelength, these curves show the relative spectral quantum yield of photosynthesis or spectral quantum efficiency.
Highest efficiency is reached in red light with maxima at 620 nm and 670 nm and lower in blue at 440 nm.
Source: McCree, 1972. (Reprinted with permission from Elsevier Science.)

Action spectra for chloroplasts and leaves

To study the effect of pigments, CO_2 uptake or the oxygen production during photosynthesis is determined from intact chloroplasts or leaves. Using different wavelengths, the same amount of light is supplied to trigger photosynthesis. Plotting oxygen production or CO_2 uptake against the various wavelengths, results in a so-called **action** spectrum. The action spectrum of the chloroplasts (Level 2) in Figure 3.17 corresponds fairly well with the measured **absorption** spectrum, except in the area where the carotenoids absorb. The action spectrum between 450 and 550 nm is lower than the absorption spectrum. This points to the fact that in that region the energy transfer is not as effective as for chlorophyll ***a*** and ***b*** alone. The absorption and action spectra for leaves prepared by McCree look completely different according to Figures 3.21 and 3.22 (Level 3).

The absorption spectrum corresponds with that of Hibiscus (Figure 3.18). The CO_2 uptake is used as starting point for the action spectra in Figures 3.21 and 3.22, and its maximum was set at 100% for red light at 670 nm.

Comparing Figure 3.17 with Figures 3.21 and 3.22 shows that the action and absorption spectra for leaves are higher for the yellow and green wavelengths compared with the spectra for chloroplasts. This points to the importance of leaf structure. The less absorbed yellow and green light, is reflected many times not only within the chloroplasts but also within the various leaf layers. Although some energy is lost in the process, most photons are ultimately absorbed by the photosynthetic pigments.

The CO_2 uptake can be divided by the amount of photons absorbed (Figure 3.21), or by the amount of energy associated with a specific wavelength (Figure 3.22). As a result, the relative rate of photosynthesis is lower in the blue light region compared to the red region. For photosynthesis, blue photons are just as effective as red photons, but not always as efficient. Blue photons contain more energy, part of which is often lost as heat radiation. This is shown more clearly in Figure 3.22 than in Figure 3.21. It is obvious that plants use orange and red light very efficiently for photosynthesis.

Research has shown that leaves can adapt to the composition of light they receive. Consequently, their action spectra may change significantly, specifically with respect to the amounts of chlorophyll and carotenoids as well as the ratio between them. This was demonstrated in radish plants raised under blue, green, and red light. Under blue light they developed 'sun type' chloroplasts and under red light a 'shade type', containing more chlorophyll and carotenoids. Radish can adjusts itself to different light compositions, but wheat and rice can not. The quantum efficiency of radish is highest under blue light and at light saturation (Curve 2 in Figure 3.23). Plant species which cannot adapt themselves and have the highest efficiency in red light, should receive as much red light as possible for the highest rate of photosynthesis.

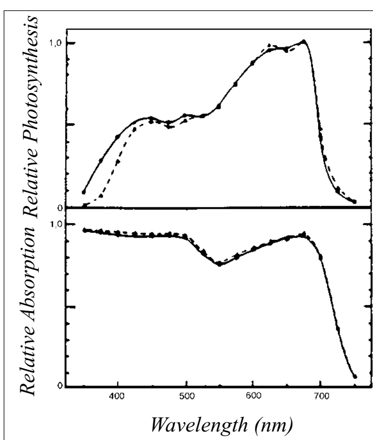


Figure 3.22. Top. ***The action spectrum*** *of a wheat leaf based on the uptake of CO_2 divided by the amount* ***energy*** *absorbed per wavelength. Note: In Figure 3.21 photosynthesis is rated differently, viz. by the absorbed* ***photons*** *or quanta. In comparison with Figure 3.21 the curve in Figure 3.22 is lower in the blue and green colour band where spectral efficiency is lower. Another difference is that the top is higher at 670 nm.*
The examined wheat was grown either in the field (- -) or in a climat chamber (–). In the blue to ultraviolet colour band photosynthesis activity of the field grown crop is lower than that of the climat chamber. This is mainly caused by the influence of the epidermis which is adapted to outdoor conditions.
Bottom. Light absorption *of a leaf, level 3, similar to Figure 3.18.*
Source: McCree, 1972.
(Reprinted with permission from Elsevier Science.)

Action spectrum of a crop

The action spectrum of a crop corresponds to the photon flux between 400 and 700 nm (Figure 3.13). There is a linear relationship, unlike the relationship for individual leaves or chlorophyll.

In summary

The degree of absorption of photons in the PAR waveband by a leaf is virtually independent of the wavelength. However, in the yellow and green light regions the absorption is lower depending on plant species and development stage. The shape of the action spectrum closely resembles the amount of absorbed photon flux. Photons in the PAR waveband are equally effective, but not equally efficient. It is important whether leaves and chloroplasts can transform themselves from "**shade**" to the "**sun** type" or vice versa. Plant species with "shade type" leaves and unable to adapt to brighter environments, have the highest rate of photosynthesis when grown under supplemental lighting with the orange-red light of HPS lamps (600-700 nm).

Light units to quantify photosynthesis

Returning to this subject later, it is useful to discuss some light units here.

PPF

PPF (Photosynthetic Photon Flux) expresses the number of photons (with wavelengths between 400 and 700 nm) falling on a certain surface per unit of time: $\mu mol\ m^{-2}\ s^{-1}$. This unit is based on the photochemical principle that the absorption of one photon activates one chlorophyll (or carotenoid) molecule. This process takes place in the chloroplasts during photosynthesis.

Watt

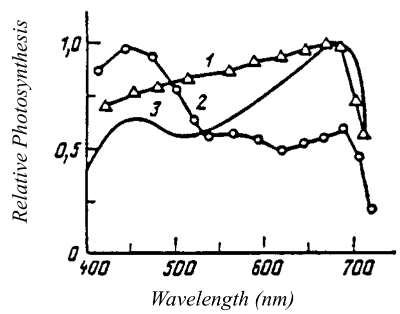
The unit *watt per* m^2 expresses the amount of radiant energy received per unit of surface area ($W = J\ s^{-1}$). For plant lighting, we are interested in the radiant energy in the *Photosynthetically Active Radiation* (***PAR)*** waveband alone (between 400 and 700 nm). In other cases, we are interested in the radiant energy contained in solar (or short wave) radiation (approximately between 300 and 3,000 nm). It is important to clearly indicate for which waveband the radiant energy is expressed. In addition, a shortcoming of expressing the radiant energy for the PAR waveband is that the different colors of the light are not taken into account. As a result, differences among light sources may occur as far as the numbers of photons emitted per amount of radiant energy released. For example, daylight with a clear blue sky provides per watt of radiant energy in the PAR waveband 4.6 $\mu mol\ m^{-2}\ s^{-1}$, while light from a high pressure sodium lamp provides 5 $\mu mol\ m^{-2}\ s^{-1}$ per watt of radiant energy in the PAR waveband, a difference of 8%.

Lux

Lux (= *lumen* per m^2) is used to express the visual light intensity. *Footcandle (ft-c)* is the imperial unit *(1 ft-c = 10.76 lux)*. It is not based on the plant's spectral response, but on the human visual spectral re-

Figure 3.23. ***Action spectra*** *for photosynthesis of radish leaves (1 and 2), based on three action spectra of leaves coming from plants grown separately in blue (400-500 nm), green (500-600 nm) and red (600-700 nm) light in different intensities:*
1. 50 $W\ m^{-2}$;
2. 200 $W\ m^{-2}$ (light saturation);
3. action spectrum according to McCree.

Leaves grown in the different colour bands, are optimally adapted to those wavelengths. The action spectra (1 en 2) differ from the general action spectrum of McCree (3). Radish is able to adapt itself to different light bands resulting in a quantum efficiency highest in blue at 50 $W\ m^{-2}$.
Source: Tikhomirov et al., 1987.



sponse. Thus, from a plant physiological point of view this unit is less useful (Bakker, 1997b; Van Rijssel, 1999), especially when the light source is not identified.

The human eye is most sensitive in the yellow-green color region around 555 nm. At 380 nm and 720 nm, the sensitivity is nearly zero. The sensitivity of the human eye is shown in Figure 3.6. The sensitivity of the human eye has been internationally agreed upon, along the following guidelines:

- at **555** nm, the number of lumen per watt is **683**,
- at **675** nm, the number of lumen per watt is **30**,

while the photosynthetic action spectrum peaks between 600 and 700 nm.

Note that the amount of light (expressed as *lumen per watt*) depends on the wavelength. For this reason, there is no unique relationship between the visual light intensity (*lux*), the radiant energy ($W\ m^{-2}$), or PAR ($\mu mol\ m^{-2}\ s^{-1}$) for all light forces.

The effect of high-pressure sodium lamps on photosynthesis, compared to average daylight, is overestimated by approximately 50% when the same light intensity (expressed in *lux*) is used as starting point (see box).

Comparing high pressure sodium lamps with sunlight when expressing the light in lux.

At 1000 lux, a SON-T Plus 400 W lamp provides 11.76 $\mu mol\ m^{-2}\ s^{-1}$ and daylight 17.86 $\mu mol\ m^{-2}\ s^{-1}$.
In other words, for the same photosynthetic response 1,000 lux of daylight and 1,519 lux of SON-T Plus lamp light is needed.
For reference: 1 $\mu mol\ m^{-2}\ s^{-1}$ of SON-T Plus lamp light corresponds with 85 lux and 1 $\mu mol\ m^{-2}\ s^{-1}$ of sunlight corresponds with 56 lux.

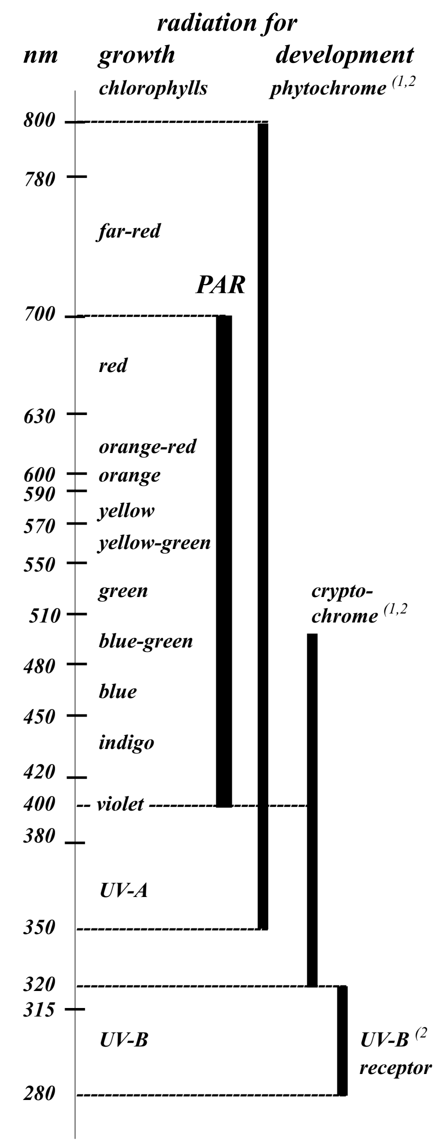
3.3 High and low radiation, growth and development

Introduction

Radiation (light) is an important environmental factor that controls plant growth and development. A principal reason for this, of course, is that light causes photosynthesis. Quite independent of photosynthesis, numerous other effects of light can occur (Figure 3.29). Most of these effects control the appearance of the plant or morphogenesis (=origin of form).
The control of morphogenesis by light is called: ***photomorphogenesis***. Some examples are light-dependent germination of seed, stem elongation, leaf initiation and expansion, orienting of leaves and stem to light (*phototropism*). For light to control plant development, the plant must first absorb the light. There are different kinds of photoreceptors known to affect photomorphogenesis in plants. The most important are phytochrome, cryptochrome, UV-B-photoreceptor, see box. Phytochrome plays a key role in light-regulated vegetative and reproductive development.
Responses to the length of the night are called: ***photoperiodic*** responses.
In greenhouse crop production, supplemental lighting is often used to improve plant growth (assimilative lighting), or to manipulate plant development (photoperiodic lighting). The latter involves manipulation of daylength, which stimulates flowering (long-day plants) or, in contrast, keeps plants vegetative (short-day plants). Applications are found, for example, in plant propagation, seedling development, and production of vegetable and ornamental crops.
The use of supplemental lighting is usually necessitated by the strong decline of light in the winter months, resulting in decreased growth, requiring longer growing periods and resulting in lower yields and reduced quality. To keep these aspects at high levels, extra assimilative light is supplied. Careful economic calculations are required to determine whether the use of supplemental lighting is feasible. Data for these calculations are frequently provided by studies conducted at research facilities and tissue culture growth rooms, in which sunlight is totally replaced by artificial light. These types of studies require sophisticated lighting systems to provide the desired light intensity and spectrum. Without sunlight, the supplemental lighting system needs to provide a complete spectrum. High-pressure sodium or high-pressure mercury lamps, for example, do not have this characteristic, while some fluorescent lamp types do.
Lighting to stimulate growth requires much more light intensity than photoperiodic lighting. Depending on the plant species, this difference can be 1,000-fold. To achieve this, different types of lamps are used. For example, high-pressure sodium lamps are frequently used to stimulate plant growth, while incandescent lamps are used for photoperiodic lighting. Sometimes one type of lamp can be used for these purposes. For example, for chrysanthemums (a short-day plant) high-pressure sodium lamps can be used. The effects of lamps on plant growth and development depends on the radiation spectrum emitted from the luminaires. Photosynthesis is promoted by light with wavelengths between 400 and 700 nm (PAR). Photoperiodic responses are the result of radiation with a wavelength between 320 and 800 nm. From a plant physiology point of view, different processes are being manipulated.

Radiation for growth and development

Light for plant growth is defined as photosynthetically active radiation or PAR in the wavelength band of 400-700 nm with high intensity. On the contrary for photoperiodic (1 and photomorphogenic (2 control a low intensity is sufficient, in the wavelength band of 280-800 nm.



Growth and chlorophyll

Light provided to stimulate plant growth is absorbed by pigments in chloroplasts. There, conversion takes place of light energy into chemical energy, which is fixed in sugars. In addition to the fact that these sugars can be used for respiration, they are the building blocks for other, more complicated compounds, such as DNA, proteins, lipids, starch and cell wall components. In what ratios and for which growth and developmental processes they will be produced, depends on a number of factors, such as temperature and light conditions. Pigments involved in the plant's photoperiodic response are responsible for adaptations to light.

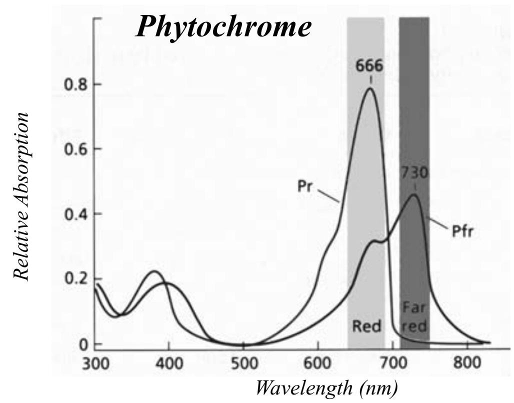
To stimulate plant growth, light intensity and light sum are important parameters. The light sum is defined as the daylength or lighting period multiplied by the (average) intensity. For example, in The Netherlands under outdoor conditions during the period between mid-April and mid-August, the light conditions are sufficient to obtain good quality and yield. The highest yields are often obtained in June and July, but they are not necessarily maximum yield. The question is under which conditions maximum yields can be obtained. For maximum yields, cultivation techniques and growth factors (for example, plant spacing, light, temperature, humidity, and carbon dioxide) should be optimized.

Without this optimization, the positive effects of adding more supplemental light can be diminished due to high growing temperatures. Plant densities should be adjusted as much as possible according to the season to allow maximum light interception. The optimum leaf area per square meter depends on the available amount of light. However, light requirements vary strongly from crop to crop, even from cultivar to cultivar. In a subsequent chapter this will be discussed in greater detail. Next, a few general principles are described.

For many crops, light saturation of leaf photosynthesis is reached at 500 $\mu mol\ m^{-2}\ s^{-1}$, without additional carbon dioxide enrichment. In a closed crop canopy with several leaf layers, this value may be two to four times higher. According to Acock (1978) the crop photosynthesis of many (C3) crops with several leaf layers is not yet saturated at 1,600-1,700 $\mu mol\ m^{-2}\ s^{-1}$. In Tables 5.3 and 5.4, these values are compared with the average (sun)light intensities in greenhouses. Around noon in June and July, average intensities of 700 to 750 $\mu mol\ m^{-2}\ s^{-1}$ are observed, with a daily average of 400 $\mu mol\ m^{-2}\ s^{-1}$. The maximum light intensity may reach 1,400 to 1,500 $\mu mol\ m^{-2}\ s^{-1}$.

Crops with a very high light requirement, such as rose, chrysanthemum, carnation, tomato, sweet pepper, and *Ficus benjamina* (Table 4.1) will, as a result, obtain maximum photosynthesis in summer only during a short time period or not at all. On average, these crops seldom perform at their maximum rate of photosynthesis. This is also apparent when we consider light sums. During the summer the light sums are on average 15% below the values for maximum photosynthesis. For many pot plants (with medium light requirements), the normal light conditions in the summer are usually more than sufficient, so that (some) shading is necessary.

Figure 3.24. ***Absorption spectra of phytochrome.*** *There are two interchangeable forms: P_r has a maximum absorption in red light (666 nm) and P_{fr} in far-red light (730 nm). After lighting with red light P_r is converted into P_{fr} for only 85% because both forms absorb red light. After far-red lighting P_{fr} is converted into P_r for 97%. Source: Taiz, 1998.*
(Reprinted with permission from Sinauer Associates, Inc.)



However, during the winter months much less light is available. In December, the average intensity around noon does not exceed 150 $\mu mol\ m^{-2}\ s^{-1}$. Pot plants with a low light requirements (200 to 300 $\mu mol\ m^{-2}\ s^{-1}$) such as African violet and many foliage plants, receive less light in winter than desired. In conclusion, in The Netherlands supplemental lighting has favorable effects on most crops. In addition to quality improvement, lighting also leads to increased growth, which is proportional to the light intensity and the light sum. In the end, a cost-benefit analysis will determine whether supplemental lighting will be cost effective.

Year-round chrysanthemums

Another example is the production of year-round chrysanthemums. During the winter, chrysanthemums require 222 to 333 $J\ cm^{-2}\ d^{-1}$ (PAR, short wave radiation) or 4.6 to 6.9 $mol\ m^{-2}\ d^{-1}$ for minimal growth and rapid bud initiation. However, in The Netherlands around Christmas only 2.3 $mol\ m^{-2}\ d^{-1}$ is available inside the greenhouse. For a period of 12 weeks, the light sum is less than 4.6 $mol\ m^{-2}\ d^{-1}$, and during 17 weeks less than 6.9 $mol\ m^{-2}\ d^{-1}$. Therefore, the use of supplemental lighting is worth considering, particularly when plant quality improvement levels off at light sums above 17 $mol\ m^{-2}\ d^{-1}$.

Photoperiodic lighting and photoreceptors

The following pigments play an important role during photoperiodic lighting:

- phytochrome (350-800 nm),
- cryptochrome (320-500 nm), and
- UV-B photoreceptor (280-350 nm).

These pigments help to provide the plant with infor-

Figure 3.25. ***The action of phytochrome (P).*** *Influenced by red light, the physiologically inactive form (P_r) is converted to the active form (P_{fr}). This occurs with chrysanthemums when long daylengths are provided with incandescent or high pressure sodium lamps. The effect is that flowering is delayed and plants keep growing vegetatively. During the dark period P_{fr} is degraded, or is converted back to P_r. Thus, long nights cause low levels of P_{fr} and in consequence flowering in short day plants. It would be better to call them long night plants because nightlength is decisive for flowering. Further, far-red lighting causes also the conversion P_r. This occurs in nature for example in the shade of trees or under a dense crop canopy, causing sun plants or shade-avoiding plants to enhance stem elongation rate and to inhibit branching.*

P_r **(physiologically inactive form)**
1. red light 660 nm ------------------------> P_{fr} **(physiologically active form)** ------------> Effects on growth and development; *e.g.* with chrysant on formation of anthocyanins, inhibition of flowering and stem elongation
2. <--------------------------- far-red 730 nm
3. <--------------------------- dark
4. Degradation

mation about light intensity, daylength, light spectrum, and light direction. These pigments are sometimes referred to as the "eyes" of a plant. They make it possible for a plant to grow and survive in different and changing environments. Most is known about phytochrome (Figure 3.24). Depending on plant species, it plays a role in seed germination, axillary bud development, elongation, flowering, dormancy, and formation of reserve organs such as tubers. Photoperiodic lighting has no direct influence on plant photosynthesis (the intensity is too low), but indirectly it can affect the development of chloroplasts and chlorophyll. If, for example, seedlings are grown in the dark, the leaves and chloroplasts do not fully develop (plants are white and etiolated). Phytochrome is often referred to as an internal clock, because it can signal changes in the daylength (Figure 3.26). Sunset (or the start of the nighttime) triggers the synchronization of this internal clock (= entrainment). Sunrise (or the start of the daytime) can also be detected with the help of phytochrome. Different plant responses are entrained to these daily rhythms, for example the diurnal movement of the leaves of Oxalis, Mimosa and bean, and the opening and closing of flowers.

Phytochrome is present in a physiologically active and inactive form (Figure 3.25). The ratio of these two forms determines the plant response. Red light activates phytochrome, while far-red light deactivates it. The inactive form (P_r, or phytochrome red) has a maximum light absorption at a wavelength of 666 nm. P_r is converted into the active form Pfr (or phytochrome far-red). The active form P_{fr} returns to the inactive form by absorbing far-red light with an optimum wavelength of around 730 nm or darkness. The transition of P_r to P_{fr} is much faster than the other way around. If there are equal amounts of red and far-red light (as is the case for sunlight), then the concentration of P_{fr} dominates. The quantity red and far-red light determines the ratios P_r/P_{fr} and $P_{fr}/(P_r+P_{fr})$. These ratios affect the response of shade-avoiding plants to stem elongation. If such a plant is placed under trees in the shadow, they start to stretch to get back into the light. Under such conditions, they receive relatively little red light, because the trees filter that out for photosynthesis. Far-red light, on the other hand, is transmitted for the most part. The active form (P_{fr}) of phytochrome, inhibiting stem elongation, is converted by the far-red light into the inactive form (P_{fr}). As a result, stem elongation is pro-

Figure 3.26. ***Phytochrome action.***

The effects of phytochrome are sometimes compared with a clock. It signals changing light conditions in the environment and passes this information on to the biological clock of a plant. In this way internal day-night rhythms are entrained to the daily light-dark cycle.

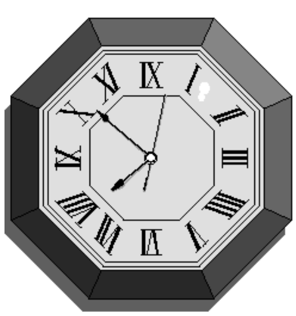
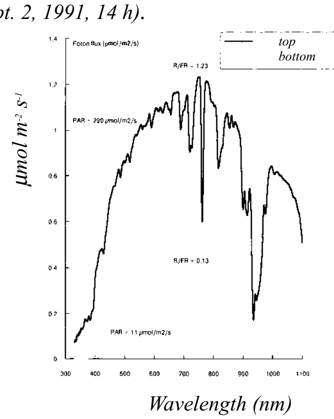


Figure 3.27. ***Light measurements above and inside a rose crop canopy*** *(PPF at Sept. 2, 1991, 14 h).*

Light intensities are 290 and 11 μmol m^{-2} s^{-1} when measured above and inside the crop, respectively. R/FR ratio is 1.23 at the top and 0.13 at the bottom. Leaves filter PAR light but transmit to a high extent far-red and infrared radiation.

Source: AB-DLO, 1991.



moted. Most horticultural crops are sun plants and respond in this way. Figure 3.27 shows how sunlight is filtered out in a rose crop. At 70 cm below the top of the canopy, the light intensity has declined by a factor of 25. Furthermore, virtually all PAR is selectively filtered out by leaves higher in the canopy. At this depth, the far-red and infrared light is still preferentially transmitted, resulting in a decline of the red/far-red ratio from above to the bottom of the canopy from 1.23 to 0.13. These measurements were taken for the wavebands of 655-665 nm for red, and 725-735 nm for far-red.

Note that these R/ FR ratio's are often measured in different wavebands, *e.g.* 640-680 nm / 710-750 nm, or 650 -700 nm / 700-750 nm. So, before comparing R/FR ratio's wavebands should be scrutinized.

Extending the daylength for a considerable length of time by lighting with incandescent lamps, increases the risk of the crop starting to stretch. This is a result of the relatively large amount of far-red light. The incandescent lamps emit more energy in the far-red compared to the red region (R / FR = 0.72 at 655-665/725-735 nm, AB-DLO).

If the red/far-red ratio decreases, the elongation of the main shoot increases while the development of the lateral shoots and branching is inhibited. In other words, the apical dominance is stimulated.

In addition, more sugars are sent to the leaves than to the roots. Leaf (pedicels) and flower stems (peduncles) become longer as well. The reverse occurs when the ratio gets larger, for example as a result of supplemental lighting. High-pressure sodium lamps (HPS) produce a large amount of orange and red light. This light stimulates the outgrowth of axillary buds. The effect of phytochrome on stem elongation is probably limited because HPS SON-T Plus lamps have a red/far-red ratio of about 2,7 (655-665/725-735 nm, AB-DLO). This causes a change in the ratio of P_{fr}/P-total. The fact that crops under HPS light tend to stretch slightly is probably due to the lack of blue light (more later) or from photoperiod. In tall, dense crops low positioned axillary buds remain dormant because they receive a relatively high quantity of far-red light. The red/far-red ratio is then smaller than 1. For comparison, the red/far-red ratio for incandescent lamp light is 0.72. For bright sunny weather the ratio is 1.15 (655-665/725-735 nm, AB-DLO). Fluorescent lamps, for example with TL-D/33 (Philips, 1996), have a high ratio of 7 at 625-700 nm/700-780 nm, which promotes branching as has been shown with poinsettia.

By supplying long-day conditions with red light alone, the development of the chrysanthemum remains vegetative. Carnations, being long-day plants, show the opposite response: flowering is advanced. For carnations, the spectrum requires far-red light as well to induce the long-day effects. Therefore, high-pressure sodium lamps are not suitable for providing long days in a LD-plant, while incandescent lamps are.

Norwegian research, performed in 1993, indicated that a short treatment with red light (PPF 26 µmol m^{-2} s^{-1}) increased the number of flowers and buds in begonia with more than 30%, compared to white, blue, or green (fluorescent) light. Further research is needed for practical applications.

Blue light and cryptochrome

Cryptochrome absorbs primarily blue and UV-A light. Its function is in phototropism (plants growing towards light), and it provides the signal for the opening of the stomata. Seedlings are able to position their cotyledons at right angles towards the incoming light so that their small leaves can be more efficient in photosynthesis. Furthermore, cryptochrome affects leaf color, which gets darker with higher concentrations. Cryptochrome also limits stem elongation by shortening internodes. For example, tomato and lettuce respond strongly to blue light. The same response was shown in the rose cultivar 'Mercedes'. When orange and white light were compared during the development of axillary buds, these shoots appeared to be 44% longer in orange light compared to white light after 6 weeks. This result can be explained from the effect of blue light present in white light. Blue light (400-500 nm) was filtered out for 100% from white fluorescent light of TL 16, Philips, resulting in orange light. In both cases the red/far-red ratio (600-700 nm/700-800 nm) was very high (7.3). Therefore, a possible effect of phytochrome can be ruled out. Thus, stem elongation is also controlled by cryptochrome (Maas, 1995).

Ultraviolet light

Few details are known on the effects of ultraviolet light (UV-B). An increase in UV-B radiation is likely due to the increasing size of the holes in and the thinning of the ozone layer. The glass covering greenhouses filters out the UV-B for the most part (Figure 3.28 and Table 3.1). But crops grown outdoors or in plastic greenhouses experience its effect (hardening off). Figure 3.29 lists some of the known radiation effects on plant growth, including the effects of UV-B.

Radiation in greenhouses

Introduction

When the effects of supplemental lighting on plant growth is being assessed, it is important to include the entire radiation spectrum both indoor and outside the greenhouse. The light spectrum produced by high-pressure sodium lamps is rather limited. However, using high-pressure sodium lamps for supplemental lighting in greenhouses usually does not result in undesirable plant growth and development. The composition of the light (UV and PAR) for greenhouses with different cladding materials is given in the Table 3.1 and Figure 3.28.

Transmissivity glass/plastics

Glass and plastics transmit approximately 90% of the total solar radiation. However, not all wavelengths are transmitted equally (Figure 3.28). Standard greenhouse glass, manufactured as floatglass (Vegla, Cologne, Germany under the brand name Planilux, transmits very little UV-B. This latter company has also developed a new type of glass transmitting UV-B under the brand name Diamant. Certain types of plastic film transmit ultraviolet radiation (UV Plus and Test 4) while other types transmit much less (Tests 5 and 6).

Figure 3.29 shows that stem elongation is highly controlled by UV-B, blue, red, and far-red light, as well as through the ratios between them. According to Hoffmann, UV-B is the cause of hardening-off effects, reduced leaf area, shorter internodes, and subsequently reduced elongation, thicker leaves with a thicker cuticle, often extra anthocyanin formation, for example in the flowers of zonal geraniums and in the leaves of Coleus.

Anthocyanin formation in Kalanchoe is induced by UV-A and increased further by UV-B. It is interesting to note that one of this plant's responses is a reduced elongation of the flower stem.

Cladding materials with reduced transmissivity of far-red light results, for many plants, in reduced elongation. On the other hand, supplementing with UV-B lamps often leads to plant damage due to excessive radiation levels.

Table 3.1. UV transmission in a mini greenhouse, measured with ultraviolet sensors (Dr. Gröbel).
UV-A: 315-380 nm, UV-B: 300-315 nm.
Source: S.Hoffmann, 1999.

	UV B (W m^{-2})	UV A (W m^{-2})	PAR (W m^{-2})	UV B (% of PAR)	UV A (% of PAR)
UV plus	4.4	19.3	232.7	1.9	8.3
Diamant	4.6	20.7	267.2	1.7	7.7
Planilux	3.7	16.9	247.8	1.5	6.8
Test 5	1.3	6.4	228.3	0.6	2.8
Test 6	0.6	1.8	223.4	0.3	0.8
outside	**6.6**	**25.7**	**289.0**	**2.3**	**8.9**
Diamant %	**70**	**81**	**92**	**74**	**87**
Planilux %	**56**	**66**	**86**	**65**	**76**

Figure 3.28. ***Radiation transmittance of glass and plastic coverings*** *(tests 4, 5, 6: PE or EVA film)*
UV-B is measured in the wavelength band 300-315 nm, UV-A 315-380 nm.
For figures, see Table 3.1.
Source: S. Hoffmann, 1999.

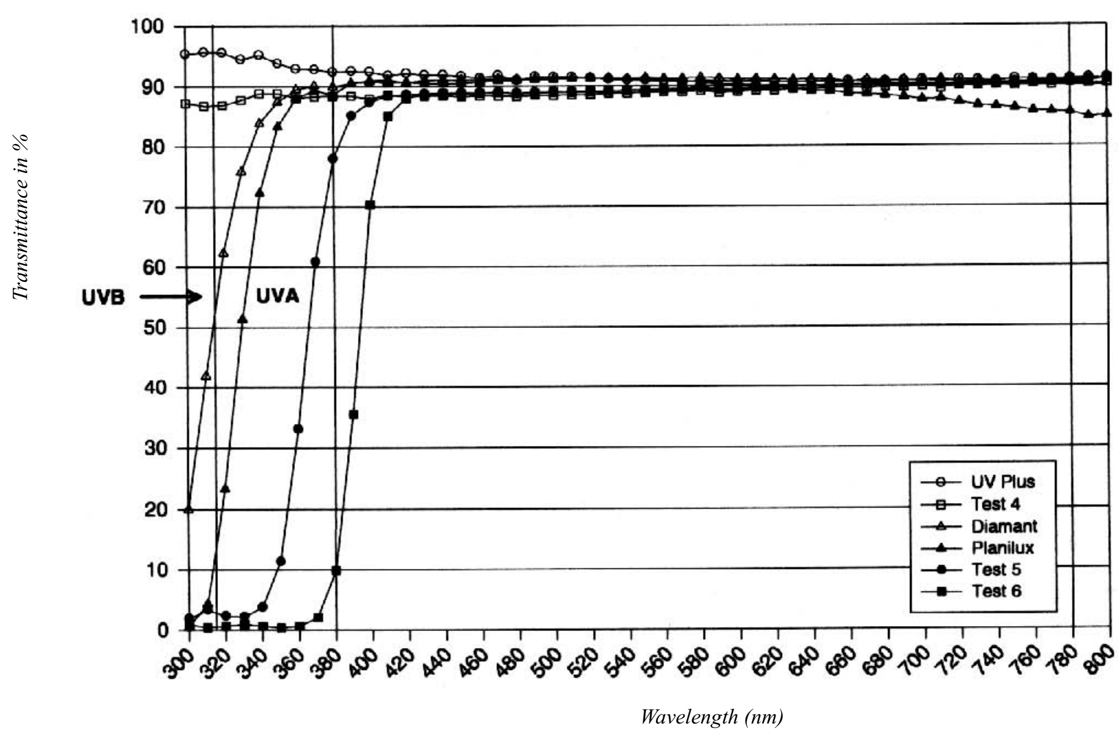


Figure 3.29. **Effects of radiation on growth and development**

	GROWTH **chloroplasts** **chlorophylls**	**DEVELOPMENT** **photoreceptors**
far-red	**PHOTOSYNTHESIS** photosynthesis (to 730 nm)	**PHOTOPERIODISM** (1 **PHOTOMORPHOGENESIS** (2 **phytochrome** (1, 2 **(350-800 nm)** P_{fr} maximum at 730 nm
red	photosynthesis	**phytochrome** (1, 2 P_r maximum at 660 nm
orange	photosynthesis	
yellow	photosynthesis	
green	photosynthesis	
blue	photosynthesis	**B/UV-A 500-320 nm** **(cryptochrome)** (1, 2 maxima at 365 and 445 nm
indigo		
violet	photosynthesis	
ultraviolet A		
ultraviolet B		**UV-B 320-280 nm** (2
ultraviolet C		

EFFECTS

Low red/far-red (R/FR) ratio and supplemental lighting with far-red result in:
- elongation, increased leaf area, decreased leaf thickness, thinner cuticles, shade-avoiding response.
- reduced branching due to inhibition of outgrowth of axillary buds; a short FR-lighting (LED) interval at the end of the day inhibits axillary bud outgrowth in e.g. rose cuttings (Moe, 1985).
- the inhibition of flower initiation is cancelled in SD-plants; disappearance of apical dominance, elongation.
- inhibition of seed germination in seeds requiring light; phototropism; closing of the stomates.
- shade-avoiding reactions of sun plants; increased elongation (etiolation) with smaller leaves.
- increase of gibberellins and decrease of auxins in some plant species; occasionally increase of anthocyanin.

High red/far-red (R/FR) ratio and supplemental lighting with red light result in:
- inhibition of elongation in sun plants.
- release of inhibition of axillary buds and branching are stimulated in roses (SON-T: high R/FR).
- increased 'sink'-effect in roses; meristematic tissue irradiated with red light receive more sugars.
- stimulates flower initiation in LD-plants (far-red is often also required).
- delay of flower initiation in SD-plants, increased apical dominance; inhibition of outgrowth of axillary buds.
- stimulates adventitious root formation in rose and chrysanthemum.
- prevents senescence (yellowing) in alstroemeria leaves.
- partly prevents bud drop in hibiscus during transport if additional lighting is given with cold red light (LED, 4 μmol m^{-2} s^{-1})
- stimulates fusion after grafting with LED (2.6 W m^{-2}).
- causes light requiring germination of seeds.
- phototropism; opening of stomates and increase in the number of stomates.
- reducing leaf area while increasing leaf and cuticle thickness, sometimes increase of anthocyanin.

- reduction in stem elongation, thicker and darker leaves, shorter petioles.
- anthocyanin formation.
- export of assimilates from chloroplasts for metabolism.
- opening of stomates.
- stimulates flower initiation in the qualitative LD-plant Arabidopsis, also blue + far-red, red + far-red.
- phototropism.

- in collaboration with phytochrome, anthocyanin formation is stimulated in some plant species.
- activation of phenolic compounds which repel insects and fungi; activation of DNA repair processes.
- phototropism.

- damage to DNA, chloroplasts and membranes; decline of photosynthesis, auxin, gibberellin, cell division, and reduced cell and stem elongation; stimulates flavonoid formation, including anthocyanin specifically in the epidermis, tannins, lignin; thicker, smaller leaves, increased branching; closing of stomates; hardening off.

- fatal for most organisms; used for example for water sterilization.
- generally, UV-C does not reach the earth's surface.

4 Growth and dry mass production

4.1 Conversion of radiation into plant growth

In this section, photosynthesis and respiration are the central issues. A simple representation of photosynthesis is given in the following equation:

$$\text{Carbon dioxide} + \text{water} \xrightarrow{\text{light energy}} \text{sugar} + \text{oxygen}$$

$$6\,CO_2 + 6\,HO_2 \xrightarrow{\text{light energy}} C_6H_{12}O_6 + 6\,O_2$$

In Section 3.2 it has been shown that leaves are capable of absorbing light and using it for the production of sugars. They do this with a low conversion efficiency. As the light level increases, the efficiency decreases, because other factors become limiting, such as temperature, carbon dioxide, nutrition and water. Although sun leaves produce more than shade leaves, they work less efficiently. Both types of leaves often occur simultaneously on one plant or stem. However, whether a plant grows sun leaves or shade leaves as a result of supplemental lighting is hard to predict, because it depends on many factors such as the quantity of blue light, the light intensity, carbon dioxide concentration and daylength. Still, experimental results indicate that 'Sonia' roses subjected to 20 h lighting grow leaves with a sun leaf character. In winter these leaves have a lower rate of photosynthesis compared to shade leaves. How important this is for an entire crop, should be investigated further. A cross-sectional view of sun and shade leaves is given (Figure 4.1 and Figure 3.20). First the light has to pass the epidermis to reach the tissues with chlorophyll. The convex epidermal cells work as lenses. As a result, the quantity of light reaching the chloroplasts is many times greater than that in the immediate environment. Most chloroplasts are present in elongated cells underneath the epidermis, also called palisade parenchyma cells. Compared to shade leaves, these parenchyma cells in sun leaves are packed more closely together. Moreover, there are often several layers of chloroplasts in one cell (Figure 4.1).

Total light absorption is a result of both direct and indirect light resulting from reflections between cells or even inside the chloroplasts. In the chloroplasts, different pigments are present that are photosynthetically active: chlorophyll ***a*** and ***b*** as well as carotenoids. Ultimately, all light energy is led to chlorophyll ***a***, a pigment directly involved in the light responses, see also Section 3.2.

4 GROWTH AND DRY MASS PRODUCTION
4.1 Conversion of radiation into plant growth
4.2 Growth factors

Growth is increase in mass or volume, as a result of cell division and cell elongation. Growth is measured in length, diameter and mass, the latter usually as fresh and dry mass. Because of varying quantities of water in plant parts, it is preferred to use dry mass as reference point for growth measurements. Increase in dry mass means a positive difference between formation and decomposition of compounds. The photosynthesis produces building stones for more complicated compounds, in which N, P, Ca, Mg, Fe and Mg can participate.
Decomposition is here meant to be the combustion of e.g., sugars via respiration, a process greatly influenced by temperature.

Figure 4.1. Sun (a) and shade leaves (b-d) of a maple tree. *Note the elongate palisade parenchyma cells in the sun leaf (**a**), full of chloroplasts, as well as the thick cuticle on top of the upper epidermis.*
*The shade leaf (**b**) is from the center of the tree, while (**c**) and (**d**) are from the bottom of the tree. The latter leaves increasingly have a more open and loose structure. In addition, leaves get thinner, because the parenchyma cells get shorter. Occasionally a second layer of those cells disappears. They contain fewer chloroplasts.* Source: Salisbury, 1992.

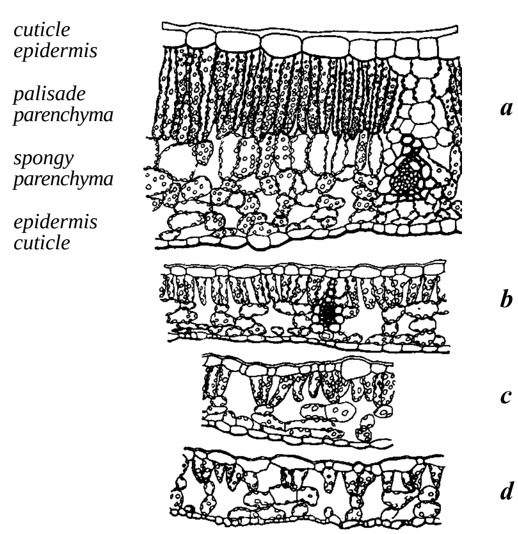
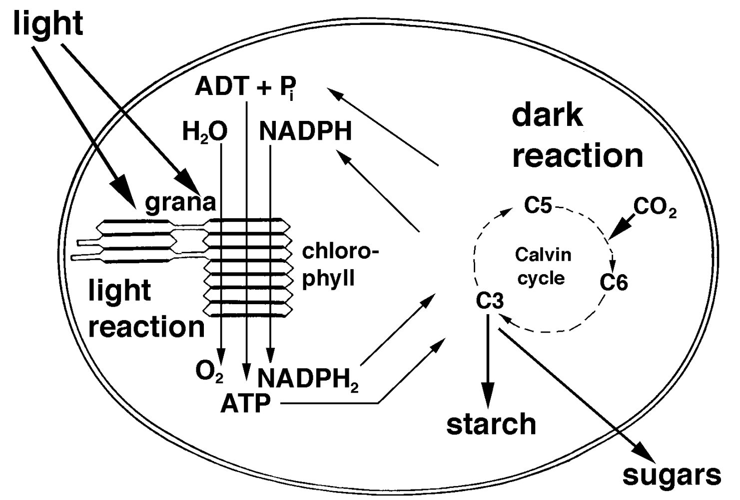


Figure 4.2. ***Chloroplast.***



The chloroplast contains a number of grana (10-50), which consists of a stack of several discs with the chlorophyll, and a syrupy solution called stroma. The grana are often interconnected by stromal lamella. Within the chloroplast, there are 2 types of reactions taking place, namely the light reaction (grana) and the dark reaction (stroma).
1. The light reaction forms high energy compounds such as ATP and $NADPH_2$.
2. The dark reaction is where CO_2 is carboxylated (=fixed) to a C_5 (RuBP) molecule through the help of the Rubisco enzyme. In order to make this process go through a cycle (Calvin cycle), one needs high-energy compounds. The latter process occurs in the stroma of the chloroplast.

Light energy, which is not utilized by the pigments, may be released as heat and radiation, the latter in the form of fluorescence. In fluorescence, light is emitted with a wavelength longer than the original absorbed light. It changes mostly into far-red (FR) or infra-red (IR) light. In the latter case, the plants appear to have a deep-red blush. This can be quantified and to a certain extent is a measure for the plant's vitality. The more a plant is fluorescing, the lower its keeping quality may be. Several research groups are currently investigating this.
During carbon dioxide assimilation or photosynthesis, carbon dioxide is fixed in chloroplasts and incorporated into carbohydrates such as sugars. This requires energy, which is supplied by light. The light absorbed by the chlorophyll is converted into chemical energy and fixed in high-energy (light response) compounds (Figure 4.2). These compounds (ATP and $NADPH_2$) release their energy in the so-called Calvin cycle in which carbon dioxide is fixed (dark reaction). As the name indicates, the latter reaction does not need light (Figure 4.2). Moreover, the five enzymes operative in the Calvin cycle appear to be activated by light. One of these is the enzyme *Rubisco*, which is responsible for the fixation of carbon dioxide. Thus light activates the entire chemical apparatus.
The Calvin cycle is a continuous number of chemical reactions resulting in carbohydrates (sugars). Carbon dioxide (CO_2) with one single carbon atom is joined with a five-carbon compound (C_5). The C_6 thus developed is subsequently split into two compounds with three carbon atoms (C_3). One of the C_3 is then changed into a C_5, which makes the cycle complete. While the other C_3 compound is used for the production of sugars. This could be in the form of starch which is made up of two C_6 glucose sugars inside the chloroplast, or outside as sucrose. Sucrose consists of two C_6 sugars (glucose and fructose) and acts as energy source and building stone. It is readily translocated through the phloem to growing tissues for the formation of new cell compunds, *e.g.* cellulose, present in the cell walls.
The chemical conversions within the Calvin cycle (dark reaction) are very temperature sensitive while those of the light reaction are not. For photosynthesis is heat energy required, which should be adjusted as much as possible to light and carbon dioxide concentration. Thus the photosynthesis achieves its highest performance, since the photosynthetic capacity is determined by the rate of the dark reaction. During the light reaction of photosynthesis is water splitted by which oxygen is formed, see Figure 4.2.

Rubisco
Rubisco is an enzyme, which facilitates the fixation of CO_2 in chloroplasts. It is the most common enzyme in green plants as it represents about 40% of all the soluble proteins in the leaves. This enzyme is activated through blue light. However, Rubisco can also oxygenate the C_5 molecule into a C_2 and C_3 molecule in case of high O_2/CO_2 ratios (e.g. low CO_2 concentration).

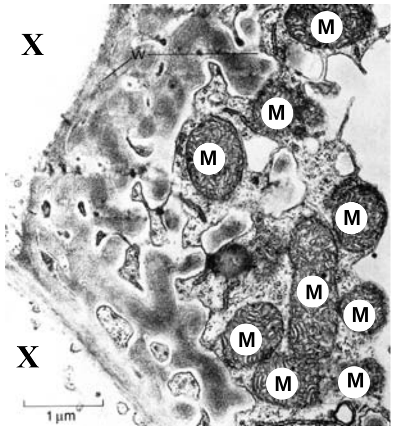
Respiration

The overall respiration reaction is often presented as the opposite of photosynthesis (although the reactions are different from photosynthesis):

sugar + oxygen	----> carbon dioxide + water + energy
$C_6H_{12}O_6 + 6\ O_2$	----> $6\ CO_2 + 6\ HO_2 +\ 32$ ATP

Besides sugars, lipids and proteins may also be oxidized to obtain energy. This energy is fixed in the compound ATP, which can be used for energy-requiring processes, such as maintenance respiration, uptake of nutrient elements or repair activities and growth.

Figure 4.3. ***A cell with many mitochondria (M).***
*Mitochondria are the energy production units of the cells. This cell is located next to xylem (**X**) from which water and nutrients are taken up to transport to other cells. This transport requires lots of energy.*
Source: Ridge, 1991.



Growth and maintenance respiration

Energy is not only required for the formation of new cells during growth and development, but also for repair or replacement of all types of cell parts.

The respiration takes place in special structures in the cells, the so-called mitochondria (Figure 4.3). These are the power stations of the cell in which ATP is formed. Oxygen is also needed for this process. ATP is also used by humans and animals to provide the muscles with energy. A large portion (30 – 60%) of the sugars formed during photosynthesis, is broken down within 24 hours. This respiration takes place day and night, even in cell tissues without chlorophyll and is called dark respiration. In the tropics, under high night temperatures, as much as 70 or 80% of the photosynthates is lost via respiration. Generally, the respiration rate doubles when the temperature is increased by 10°C, while it starts to decline when temperature exceeds 30°C. The optimal temperature for photosynthesis is lower than that for respiration. Developing plant parts have a higher respiration rate than older ones. Carbohydrates are also used in another way, during the so-called photorespiration.

Photorespiration

Contrary to the dark respiration, which continues night and day, photorespiration only takes place during the light period. During the dark reaction of the photosynthesis, carbon dioxide is fixed to a C_5 compound (carboxylation), resulting in a C_6 compound. This reaction is realised with the help of the enzyme *Rubisco*. Under certain conditions (high O_2/CO_2), *Rubisco* may, however, also be responsible for the oxidation of the C_5 compound. In the latter case, the C_5 compound is split into a C_2 and C_3 compound, of which the C_2 compound is further split into CO_2 and energy. This latter process is called light respiration.

Under normal circumstances *Rubisco* binds carbon dioxide much more often than oxygen. But this changes as temperature, light level and oxygen content increase. The ratio between the CO_2 and O_2 contents shifts in favor of O_2, resulting in a higher photorespiration. During the day, the oxygen content in the plant increases automatically via photosynthesis in which oxygen is produced.

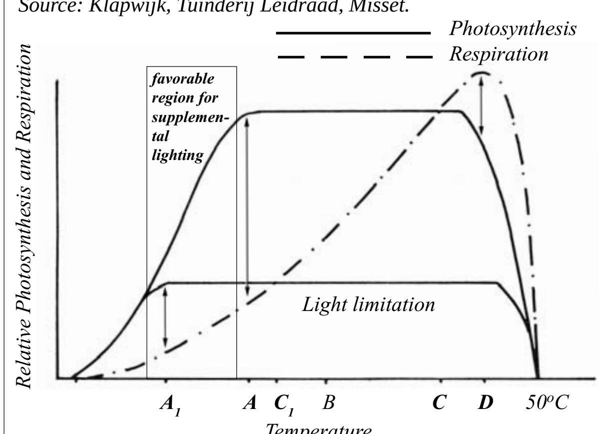
When the carbon dioxide concentration in the greenhouse is increased, the CO_2/O_2 ratio within the leaf of the plant increases and the photorespiration decreases. Mortensen and Moe (1983) showed that a reduction of the oxygen content in air to 2% resulted in an increase of the net photosynthetic rate (photosynthesis minus respiration) by more than 50% compared to ambient oxygen (20% O_2). Reduction of the oxygen content is not practically feasible in a greenhouse, but an increase of the carbon dioxide concentration is.

With a normal oxygen content (20%) and 1500 ppm CO_2, the photosynthetic rate increases with 64% compared to ambient CO_2. This is simply due to the fact that the CO_2/O_2 ratio in the plant increased. Higher yields through CO_2 enrichment are therefore mainly the result of the suppression of photorespiration. In addition, however, extremely low, limiting CO_2 concentrations in the crop are to be avoided.

Growth

Most growth (dry mass accumulation) can be obtained by maximizing photosynthesis and minimizing respiration. In Figure 4.4, that point is reached at temperatures ***A_1*** and ***A***, depending on the light intensity. At those two points the dry matter gain is the highest. Whether these are optimal for quality and growth rate, for example, can be questioned. On the one hand, higher temperatures result in a lower dry matter gain, while on the other hand it results in more energy production from the resulting higher respiration rate.

Figure 4.4. ***Photosynthesis and respiration in relation to temperature.***
*At low temperatures, photosynthesis increases much faster than respiration with increasing temperature. At temperature **A**, the net gain is the greatest; at temperature **C**, no extra sugars are available for growth; at **D**, there is a net loss. Similar processes take place under limited light conditions (winter), but at lower temperatures (**A_1** and **C_1**, respectively).*
Source: Klapwijk, Tuinderij Leidraad, Misset.



Cell division and development rate of leaves and flowers will also increase. Consequently, the crop will start flowering sooner, but chances are that flowers and leaves are smaller. The effect of the temperature on root respiration can be significant as well. Experiments in rose cultivation indicated, for example, that a temperature increase of the substrate from 17 to 21ºC, reverses the effect of supplemental lighting completely (Bakker, 1997a).

Photosynthesis responds differently to temperature compared to respiration. Respiration rate usually peaks between 30 and 35ºC, and then declines rapidly. In contrast, photosynthesis reaches a maximum sooner and subsequently remains at a rather constant level. The upper limit is related to other growth factor inhibiting a further increase of the photosynthesis above a certain temperature. Liebig's Law (law of the limiting factor) applies for light being the limiting factor (Figure 4.4). Under low light levels, maximum photosynthesis is reached at A_1 while under higher light levels this happens at A. Another conclusion is that the difference between photosynthesis and respiration is strongly increased with extra light because the photosynthesis in the section between A_1 and A increases much faster than the respiration. In the following section, the interaction between temperature, light intensity and carbon dioxide concentration will be discussed in greater detail.

Other factors which affect dry matter production are:

a. Stomatal closure.

This results in a decrease of uptake of carbon dioxide by the leaf, which results also in a decrease in transpiration and subsequently in an increase of leaf temperature. If the latter occurs, respiration increases and, thus, dry matter production decreases.

b. Inadequate export of sugars from the chloroplasts, which counteracts photosynthesis.

Excessive accumulation of starch may even lead to decomposition of chlorophyll.

c. Reduction of (old) foliage, which limits the use of sugars for maintenance respiration.

A technique applied in rose cultivation, for example, is to prune away the non-productive parts that only consume sugars during the winter months. The maintenance respiration is reduced as a result, so that the surplus of sugars in increased. This, in turn, is of benefit for the production. In some situations the oxidation of sugars in the winter may be greater than the production, resulting in negative growth. Optimum production results from a balance between production (photosynthesis) and consumption of sugars (respiration).

d. For optimal growth and development, maximum leaf area is necessary for maximum light absorption.

The leaf canopy can be compared to a sugar factory. If the slightest detail goes awry, it will cost productivity. For every crop or planting date, the appropriate plant density must be determined in order to reduce the competition for the amount of available light.

Leaf Area Index (LAI)

Leaf Area Index (LAI) is defined as the total leaf area (m^2) per m^2 of soil surface. The optimal values for greenhouse crops in The Netherlands are between 3 and 5, irrespective of the CO_2 concentration (Challa, 1995). In addition to light intensity, the optimum LAI strongly depends on the position of the leaves. Plants with slanting leaves have a higher optimal LAI than those with a more horizontal position. For this reason, the optimal LAI of wheat can be as high as 30. A LAI of 3 means 3 m^2 leaf area per m^2 of soil surface. The more leaf layers a crop has, the higher the light absorption becomes. Reflected or transmitted light is eventually absorbed for a large part, leading to an increase in photosynthesis.

Growth and production of crops are closely related to LAI. For example, from the end of February onwards, additional shoots are maintained in tomato crops to increase the LAI and consequently the yield.

Gross and net photosynthesis

Sugars which are produced during the process of photosynthesis, are partly consumed by the respiration (both light and dark). The respiration is required for both growth (increase in dry matter) and maintenance of the existing tissues/cells. The measurements of photosynthesis is done by measuring the CO_2 exchange over time for a given leaf surface area by specifically developed equipment. Unfortunately, the measurements taken during the light period includes both the overall results of photosynthesis (CO_2 uptake) an respiration (CO_2 release). Consequently, this measurement is referred to as net photosynthesis, expressed as the net assimilation rate in $CO_2/m^2/$ sec. Gross photosynthesis can not be measured in situ and is more an abstract term. In order to estimate this (in addition to the net photosynthesis measurement), one has to determine both the photorespiration as well as the dark respiration during the light period. The latter two factors can not be easily measured. Dark respiration can be measured in the absence of light but it is questionable whether measurements of the dark respiration are the same for both the dark and the light period. Photorespiration can be partly based on Rubisco kinetics (and CO_2/O_2 ratio), but depend also on a number of assumptions, which are beyond the intent of this book, and can not be determined.

In conclusion, net photosynthesis can be measured with a special instrument and is often expressed as net assimilation rate (NAR), or net carbon exchange rate (NCER). Gross photosynthesis can not be measured with any present-day equipment and only an estimate can be given. Some older reports gross photosynthetic rate, and was often determined as the sum of net photosynthetic rate and dark respiration rate, but this value is likely inaccurate.

As the crop grows taller and denser, the effect of more leaves decreases, because the light intensity penetrating the lower canopy is reduced. With a LAI of more than 5, the net growth rate often no longer increases. In Figure 4.5, the curve in the middle (60% of full sunlight) more or less represents greenhouse conditions. The competition for light continuously increases as the crop grows. In the Dutch tomato production system, every week the three bottom (non-active) leaves are removed. While at the top, three new leaves are added so that the total leaf area per plant remains constant.

The dry matter production per m^2 may be slightly increased through higher plant densities, but often the crop quality will decline. For example, in pot plants this is manifested in the plant shape ('store pipe' look). Above a certain plant density, the growth rate changes from exponential into linear. Plant spacing should be increased when the plant shape indicates the optimum LAI is surpassed.

The effect of light on (gross) photosynthesis is shown in Figure 4.6. It shows that photosynthesis increases with increasing LAI. But in relative terms, the effects decline. At a LAI of 1, the curve reaches saturation sooner than in the case of LAI of 3 or 4. The saturation of the gross crop photosynthesis shifts to higher PPF. The range of light intensity from 0 to 1,500 μmol m^{-2} s^{-1} is of interest for many temperate climate regions. For example, in The Netherlands in December, the maximum light intensity is approximately 150 μmol m^{-2} s^{-1}, while in September and March it is 520 and 430 μmol m^{-2} s^{-1}, respectively (Table 5.4). Supplemental lighting is generally applied when during the day the light intensity remains below 500 μmol m^{-2} s^{-1}. Figure 4.7 shows that the photosynthesis increases (almost) linearly over a large range of light intensities. However little gain is expected under low light conditions (winter) with a LAI greater than 3 and without CO_2 supplementation.

The growth promoting effects of carbon dioxide enrichment at a LAI of 3 are well documented, although the benefits from a concentration above 700 ppm become relatively small. A rose crop, which, in terms of light requirements can be compared with a tomato crop, will react similarly. In winter, a maximum LAI of 3 is recommended for roses. Any additional leaves

Figure 4.6. ***The gross crop photosynthesis of tomato based on light intensity (inside the greenhouse) and four different LAI's.***
Basic conditions were 25°C and 350 dpm CO_2. The photosynthesis is expressed as the uptake of CO_2 in gram m^{-2} h^{-1}. Source: H.Gijzen, 1995.
(Reprinted with permission from Wageningen Press, Publishers.)

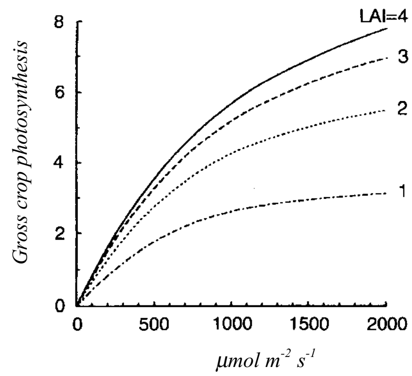


Figure 4.5. ***The influence of the Leaf Area Index or LAI on the growth rate of a crop.***
The leaf surface area per square meter of soil surface should be adjusted to the available light. The diagram represents sunflowers at a plant density of 100 per m^2. They are raised under various light levels: from 23% to 100% sunlight. The optimal LAI under full sun is 7, while at 23% of full sunlight a LAI of 1.5 is already optimal. The crop growth rate sharply declines past the optimal LAI.
Source: Leopold en Kriedemann, 1975.
(Reprinted with permission from MacGraw-Hill.)

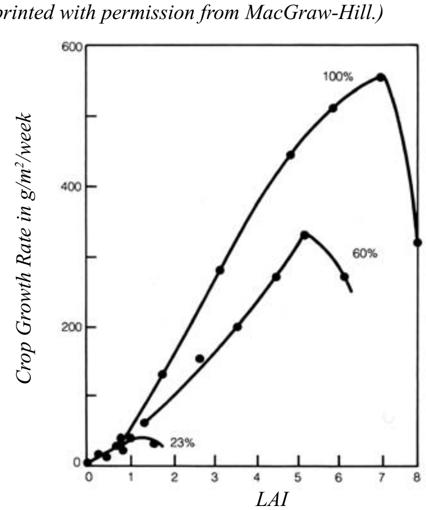
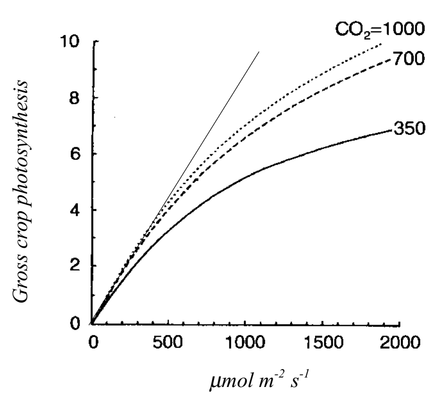


Figure 4.7. ***The gross crop photosynthesis of tomato for various light intensities (inside the greenhouse) and CO_2 -concentrations.***
General conditions were 25°C and a LAI of 3. The photosynthesis is expressed in the uptake of CO_2 in gram m^{-2} h^{-1}. These simulations were tested with a tomato crop at the Research Station for Floriculture and Glasshouse Vegetables in The Netherlands, with a light intensity of up to 1,250 μmol m^{-2} s^{-1}. The relationship between growth and light remains (almost) linear over large ranges, especially when CO_2 enrichment is implemented. In these ranges is generally lighted. Source: H.Gijzen, 1995.
(Reprinted with permission from Wageningen Press, Publishers.)



will result in a negative growth. Figures 4.6 and 4.7 show the results of crop growth simulations, using a computer program with various crops, including tomatoes.

Sun and shade leaves

Most horticultural crops are sun plants, while some foliage plant (pot plants) are grown as shade plants. This classification gives information on the rate of photosynthesis. For sun plants, photosynthesis is saturated at a (much) higher light levels compared to shade plants. So, sun plants have a potentially bigger photosynthetic capacity. The photosynthetic saturation level also depends on other factors such as temperature, carbon dioxide concentration, relative humidity, supply of water and nutrients.

Young leaves of sun plants are able to adjust themselves to different light levels through their orientation and composition of chloroplasts, an ability not present in shade plants. In both cases, however, leaves, as well as flowers, can be damaged if the light levels become too high. This damage appears as chlorosis because the chlorophyll and/or the chloroplasts are destroyed. Leaf necrosis may occur in extreme cases. The light intensity at which shading is necessary in a greenhouse changes throughout the season. During February/March, shade curtains are deployed at a lower light intensity than during summer, because shortly after winter, plant leaves are not yet adjusted to higher light intensities.

The effect of sun and shade leaves of the perennial ‘Solidago’ on net photosynthesis is presented in Figure 4.8 (A). The net photosynthesis of sun leaves (dashed line) still increases at light levels above 300 μmol m^{-2} s^{-1}, while shade leaves get saturated around that intensity (solid line). This can be concluded from the net uptake of carbon dioxide. Below 300 μmol m^{-2} s^{-1} shade leaves deal more efficiently with the light energy than sun leaves, and thus produce more sugars with the same amount of light energy. In addition, shade leaves consume fewer sugars for maintenance respiration (see arrows in Figures 4.8 A and C).

In assessing the effect of light on growth, there are two important points: the saturation point for photosynthesis as treated before and the light compensation point. The latter describes the light intensity at which the net photosynthesis is zero (see 1 and 2 in Figure 4.8 C). These characteristics describe the type of plant, and consequently points to techniques for its cultivation, with respect to screening, lighting, temperature, carbon dioxide, water and nutrition.

Light compensation point (LCP)

The net uptake of carbon dioxide is zero at the light compensation point (LCP), which implies that the production of sugars is equal to the break down (use). This is the light intensity at which the photosynthetic response curve intersects the *x*-axis (Figure 4.8 A-C).

Figure 4.8. ***Light compensation point and net leaf photosynthesis for various light intensities for sun and shade plants.*** *Source: Björkman and Holmgren, 1963 (A, B) and Horn, 1996 (C).* *(Reprinted with permission from Munksgaard Int.Publishers Ltd.)*
*The herbaceous perennial plant Solidago virgaurea was grown under two different environments (**A** and **B**). Plant **A** grows in full **sunlight**, while plant **B** grows in the **shadow**. The sun and shade plants are propagated and raised under high (dashed line) and low (solid line) light levels. Two clones were developed. The sun plants grown at low light levels (A) clearly produced shade leaves which deal more efficiently with the light at levels below 200 μmol m^{-2} s^{-1} than sun leaves (see also C). The shade plants (B), cultivated under low light levels, perform better than when raised in the full sun. Compared to A, the photosynthesis level is rather high, which means that within a given species selection can be carried out on light sensitivity, based on hereditary characteristics. This is actually being done with many glasshouse crops, such as rose and chrysanthemum, and could also be taken into account in the selection of stock plants of green plants in (sub)tropical countries. Figure **C** shows that the light compensation point (LCP) of shade plants (1) is reached at a lower light intensity than that of sun plants (2). Furthermore the sun plants appear to consume more sugars for maintenance or dark respiration than shade plants (arrow). The y-axis shows the amount of production (<0) and uptake (>0) of carbon dioxide.*

A: clone from sun plants ***B: clone from shade plants*** ***C: net photosynthesis and dark respiration of sun and shade leaves***

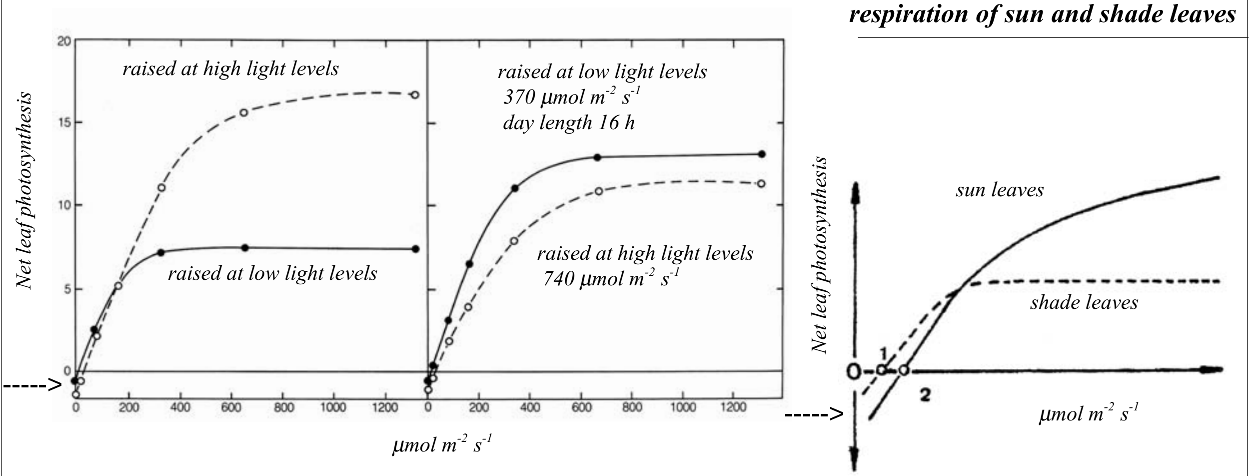


Table 4.1. ***Light compensation point (LCP)*** *in µmol m⁻² s⁻¹ at various temperatures (Fatsia, Euphorbia) and light levels during the growing period (Dendranthema). Source: Horn, 1996.*

temperature °C	Fatsia japonica LCP µmol m^{-2} s^{-1}	Euphorbia pulcherrima LCP µmol m^{-2} s^{-1}	Dendranthema 'Surf' growing light level µmol m^{-2} s^{-1}	Dendranthema 'Surf' LCP at 18°C µmol m^{-2} s^{-1}
27	-	12.0	50	2.5
24	8.0	9.4	140	19.0
21	8.6	7.9	285	27.3
18	6.8	6.1		
15	6.2	5.1		
12	5.2	-		

The LCP for different ornamental plant species and environmental factors are listed in Table 4.1.

At the LCP, the plant can maintain itself without weight loss, but both the internal and external quality often decline. The LCP of sun plants is higher than that of shade plants, but when sun plants are shaded for some extended period (several weeks), the compensation point is lowered. In this respect it may be useful for certain pot plants to acclimatize at a lower light intensity for several weeks before delivery, so that they are better able to survive under the lower light conditions in living rooms. Another conclusion from Figure 4.8 A is that tall crops (rose, chrysanthemum, tomato) should not be allowed to become too leafy. There are two reasons for this: *(i)* to prevent that full-grown sun leaves which are no longer able to acclimatize become shaded, and *(ii)* to prevent the development of too many shade leaves.

It is remarkable that the photosynthetic rate of shade plants (solid line) is higher after acclimatization to low light levels compared to shade plants grown under high light (Figure 4.8 B). This situation develops gradually from winter to spring with shade plants.

Note that roses grown under supplemental lighting with a rather low intensity (50-100 µmol m^{-2} s^{-1}) develop sun leaves (Figure 4.1 A).

Light intensity

Most greenhouse crops, such as roses, chrysanthemums, tomatoes and cucumbers have a high light requirement. This implies that the maximum light intensity for supplementary lighting will be high. In Europe, a supplemental light intensity of 20-100 µmol m^{-2} s^{-1} is common. These levels are well below the saturation level for crop photosynthesis, which is often higher than 1,000 µmol m^{-2} s^{-1}. For pot plants with a low light requirement, these values are between 200 and 300 µmol m^{-2} s^{-1}. If such crops are given supplemental lighting with too high light intensities, disorders can be expected. For example, Lorraine Begonias irradiated with supplemental lighting in the winter to a level of more than 100 µmol m^{-2} s^{-1} (supplemental light and sunlight combined), develop cup-shaped flowers as well as necrosis (Moe, 1997).

The greatest benefits of supplemental lighting can be expected during low-light periods as has been shown by research.

Lighting of cucumber with 300 µmol m^{-2} s^{-1} in Canada (52° latitude) tripled yields after five months, showed an increase of 80% using 180 µmol m^{-2} s^{-1}; and no significant effect using 100 µmol m^{-2} s^{-1}. For tomatoes, the yield was increased by 90% using 150 µmol m^{-2} s^{-1} high-pressure sodium lighting (Ehret, 1989).

For tomatoes, light saturation does not occur even at 1,400 µmol m^{-2} s^{-1} (Heuvelink, 1996). Furthermore, supplemental lighting can significantly increase cutting production from stock plants. Norwegian experiments showed that an increase in light intensity from 25 to 75 µmol m^{-2} s^{-1} during the period from October through March, produced more cuttings for begonia (49%) and chrysanthemum (58%). This increase is due to faster growth and more lateral shoot formation. In addition, subsequent root development is improved, as is the case for campanula and poinsettia. In campanula and chrysanthemum, a positive correlation has been found between the carbohydrate content and root development (Moe et al. 1988).

A large amount of energy is required for flower initiation and development. When the light sum drops below a critical value, these processes may be delayed, or this may result in the abortion of the flower buds (*e.g.* rose). The light sum for roses (day-neutral crop) can be increased by extending the lighting period to as long as 24 h. But due to the fact that the minimum light sum for rose is much higher than for chrysanthemum, higher light intensities are required for roses.

In Denmark (55° latitude), 'Frisco' roses were grown under supplemental lighting throughout the year with high-pressure sodium lamps for 20 h at an intensity of up to 174 µmol m^{-2} s^{-1}. A linear increase was observed in production (82%), length, diameter and mass of the stem and a lower number of blind shoots. Keeping quality was improved with more light as well, provided that the lighting period did not exceed 20 h

Light intensity and light sum

The light intensity, or so-called photosynthetic photon flux (PPF) is expressed in µmol m^{-2} s^{-1}, equalling a quantity of $6.023 \cdot 10^{17}$ photons.
The daily light sum is the number of photons measured per m^2, expressed in mol m^{-2} d^{-1}.
In energy terms, the intensity is expressed in watt or J s^{-1} and the daily light sum in J cm^{-2}, either as total global radiation (280-2,800 nm) or as PAR (400-700 nm).

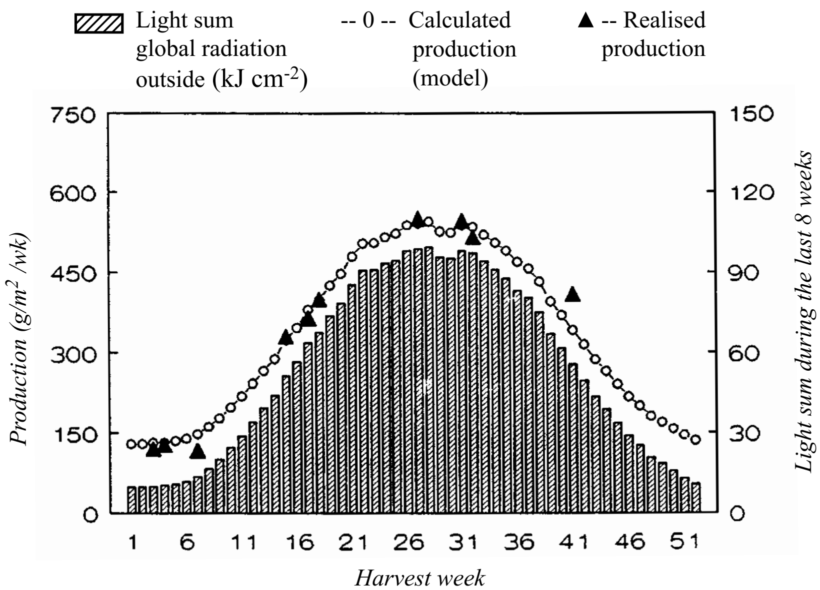


***Figure 4.9.* Relationship between growth (fresh mass) of Chrysanthemum and light sum.**

The figure shows:
- *radiation sum during the last 8 weeks prior to harvest (kJ cm^{-2}, averages over 1990-1993), bars;*
- *production (gram per m^2 per week), calculated (model) and realised (triangle)*

Source: Buwalda, Research Station for Floriculture and Glasshouse Vegetables, The Netherlands, Report 176 (1994).

(Bredmose, 1993). In Norway (67° latitude) roses are grown year-round under a supplemental lighting intensity of 180 $\mu mol\ m^{-2}\ s^{-1}$ (Moe, 1997).
Supplemental lighting can influence the length of the production period and plant quality, even under relatively low lighting intensities. This has been observed at the Research Station for Floriculture and Glasshouse Vegetables in Aalsmeer, the Netherlands, in experiments with begonias, african violets, potted miniature roses, ferns, and hydrangeas (Verberkt, 1995). Supplemental lighting of 16 to 20 hours per day at 30 $\mu mol\ m^{-2}\ s^{-1}$ leads to considerable improvements during the winter months. A higher light level (45 $\mu mol\ m^{-2}\ s^{-1}$) is often even better.
For some african violets cultivars, however, supplemental lighting can lead to brittle and compact leaves, resulting in increased risk of leaf breakage during packing. Furthermore, the plants may develop multiple growing points (side shoots). By reducing the light intensity towards the end of the production period, leaf breakage in african violets can be decreased.

Daily light sum

So far, growth was discussed in relation to light intensity, but the light sum (light intensity integrated over time) is equally important. In greenhouses, the light sum ranges between 1 and 35 $mol\ m^{-2}\ d^{-1}$. For comparison, the light sum of supplemental lighting is about 5 $mol\ m^{-2}\ d^{-1}$ when lighting is provided for 20 h at 70 $\mu mol\ m^{-2}\ s^{-1}$. This can be more than double the light sum received from natural light during the middle of winter. The total light sum can be significantly increased during other winter months as well. The ratio of supplemental lighting to the total light sum depends on the timing of switching the lamps on and off. For the total light sum, the light intensity and light sums of the global radiation (pyranometer) need to be taken into account. This will be discussed in more detail in Chapter 5.

Minimum light sum

The question is which minimum light sum is needed for adequate growth, development, and quality. As soon as this has been determined, the intensity and duration of supplemental lighting can be assessed, as well as its profitability. Shade plants grow well in an environment with approximately 5-10 $mol\ m^{-2}\ d^{-1}$, while sun plants require 20-50 $mol\ m^{-2}\ d^{-1}$ (Moe, 1997). When these figures are compared to those in greenhouses during the course of the year, the conclusion is that supplemental lighting during a major part of the year may be useful.
In many horticultural crops, relationships are known between growth rate, fresh and dry matter production, and light sum. Often the concept of LUE or light use efficiency is used (see box). The highest production is generally obtained during the summer as is shown for year-round chrysanthemum (Figure 4.9). During winter, the yields are lowest and many

Light Use Efficiency (LUE)

The LUE represents the relationship between the amount of dry matter produced by a crop and the quantity of radiation received per unit surface area, and can be expressed as:

$$LUE = \frac{\text{gram dry matter } m^{-2}}{\text{MJ PAR of PAR received } m^{-2}}$$

The LUE is a characteristic parameter for the growth of a healthy, well-developed plants in proper environment (Gosse, 1986).
If all environment conditions are optimal, the LUE is only limited by the photosynthetic metabolism of the plant.
A common value for the LUE is between 2 and 3 gram / MJ of PAR.
A rule of thumb for supplemental lighting is 2,5-3 gram / MJ of PAR (Kool, 1996).

crops cannot be produced economically without supplemental lighting. Flower and fruit initiation and development require more light, for example for rose (blind shoots), tomato and cucumber.

For tomato, there is a linear relationship between the cumulative yield (kg m^{-2}) and the total light sum (PAR). Approximately 50 MJ m^{-2} of global radiation is required for 1.0 kg fresh mass of tomatoes. This corresponds with (93% moisture content):

3.1 g of dry matter per MJ m^{-2} of PAR.

In roses, a linear relationship has been demonstrated for 'Sonia' and 'Koba'. (Figure 4.10). According to this French research the LUE for 'Sonia' is:

1.6 g of dry matter per MJ m^{-2} of PAR.

Compared with Dutch results with other cultivars, this was slightly lower than that of 'Madelon' (2.1 g/MJ) and 'Frisco' (2.7 g/MJ), (Kool, De Koning, 1996). The discrepancy between the 2 cultivars was explained by the less than optimal CO_2 enrichment for 'Madelon'.

Similar data have been reported from research with roses and pot plants, when the production is expressed per mole of light (1 MJ PAR = 4.6 mol for sunlight). During the winter months, pot plants, such as ferns, begonia and african violets, produce about: (Van Rijssel, 1997)

0.65 g dry matter per mol of PAR.

For the large-flowered rose 'Madelon' this number is:

0.53 to 0.68 g dry matter per mol of PAR.

If the percentage of dry matter is 23.4%, the **fresh mass** of 'Madelon' increases with approximately

0.61/0.234 = 2.6 g per mol of PAR.

The LUE in summer and fall is lower compared to the LUE in winter and spring. This is probably related to the harvesting method and the carbon dioxide concentration in the greenhouse. It is becoming more common to calculate the extra costs and returns of lighting on a per gram fresh mass basis. In experiments with 'Madelon', an additional yield was obtained of:

7.95 g (0.26 stems) per kWh electricity consumption.

Therefore, each additional rose would cost an extra 4 kWh. The relationship between electricity consumption and light output was found to be linear: 3.11 mol of supplemental light per kWh using a power input of 460 W for a luminaire equipped with a HPS (SON-T) lamp of 400 W (Van Rijssel, 1995).

The rule that 1% less light results in 1% less yield (at least in early Spring) is generally well known. Originally, this rule was based on results from cucumber experiments.

There are differences between the various horticultural crops with respect to the optimal (light) conditions under which they are grown. Shade plants deal more efficiently with low light levels than sun plants. Furthermore, they consume less sugars during respiration. As the light intensity increases, the photosynthesis of shade plants gets saturated sooner compared to sun plants. Because shade plants have thinner leaves than sun plants, the chlorophyll gets damaged more quickly when high light levels change suddenly. Therefore, physiological differences should be taken into consideration when using supplemental lighting.

Hendriks, Ludolph and Moe (1993) set up a classification for number of horticultural crops based on light requirements for optimal growth and development. The average light sum requirement differs considerably among crops (Table 4.2). The light requirements are also influenced by temperature, carbon dioxide concentration, light quality, air humidity, water, nutrition, etc. For the daily light sum, not only the intensity but also the photoperiod is important.

Photoperiod / daylength

The optimum length of the lighting period depends on many factors including economical plant physiological, administrative or technical areas. The lighting period is not necessarily the same as the daylength or photoperiod. When the lighting period is longer than the natural daylength, the light provided during the absence of sunlight is termed supplemen-

Figure 4.10. ***Relationship between dry matter of harvested, whole flower stems and the incident light sum (inside the greenhouse).***

On the vertical axis, the dry mass per m^2 per day is given in MJ (10^6) Joule PAR. Observations were for two cultivars: 'Sonia' en 'Koba'.
Also included is the Gosse-line, which has general validity for C3-plants, such as roses.
The light use efficiency (LUE) of 'Sonia' is 1.6 g dry matter per MJ PAR per day and 2.0 g for 'Koba'.

Source: Morisot,1996.
(Reprinted with permission from ISHS.)

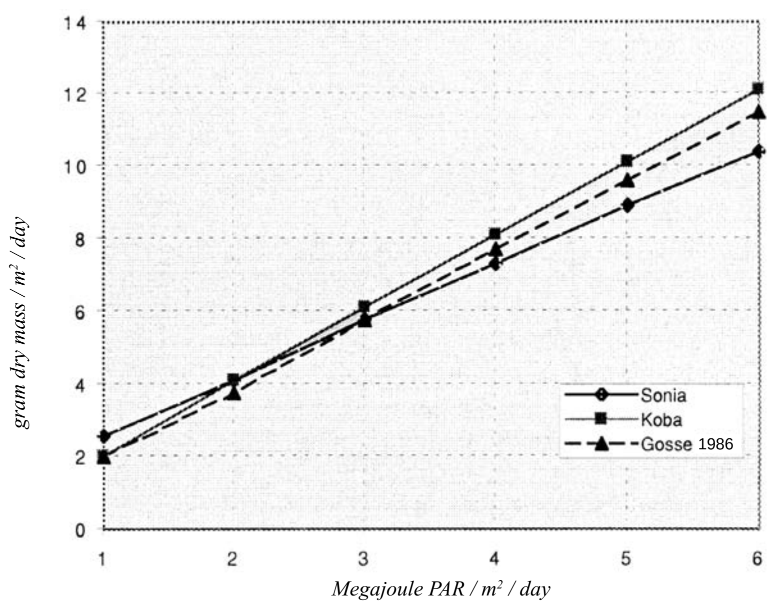


Table 4.2. ***Classification of a number of crops according to light requirements.***

Crop	Low	Average	High	Very high
Rose				+
Ficus benjamina			+	
Tomato				+
Chrysanthemum			+	
Hedera			+	
Sinningia		+		
Dieffenbachia		+		
Spathiphyllum		+		
Kalanchoë		+		
Cyclamen		+		
Begonia Elatior		+		
African violet	+			

Source: Hendriks, Ludolph en Moe, 1993.

tal lighting. For the calculation of the daily light sum, the number of hours of lighting as well as the intensity should be know. The total light sum is the light sum during natural light and supplemental lighting. Important considerations for lighting are:

1. The short and long term economic profitability.

This requires accurate estimates of the costs and benefits with respect to quality, yield in stems and in dry matter, business management, being able to grow summer cultivars, improvement or maintenance of the market position. Such analysis can help develop a lighting strategy including parameters such as equipment, intensity, and duration.

2. Physiological factors:

a. Daylength sensitivity

The maximum photoperiod depends on the daylength sensitivity. Short-day plants that are induced to flower should not be grown under long photoperiods (or rather under short dark periods), as for example with chrysanthemums (requiring a photoperiod of up to 12 hours). This means that supplemental lighting can be applied for up to 12 hours maximum. However, Begonia Elatior can, after a limited period of short-day, be grown under a long-day regime again. This will lead to higher light sums, as is possible with many daylength-neutral and long-day plants. The maximum photoperiod for these crops is often between 16 and 24 hours.

For cucumbers, flowering is delayed under a 24-hour photoperiod (Bakker, 1996). This provides an opportunity for supplemental lighting during initial plant growth, but it creates a problem during crop maturation.

For rose crops, many photoperiods have been tested. The day-neutral cultivar 'Frisco' produces more and heavier basal shoots under a photoperiod of 17 to 20 hours compared to 14 hours.

b. Biological clock

Most crops require a minimum length of the dark period. This is a natural adaptation of plants grown in an environment with alternating light and dark periods. When the dark period is shifted or continuous lighting is given, this daily rhythm is disturbed resulting in negative effects on crop growth and development. In addition to chlorosis or necrosis in the leaves, disruptions in the closing mechanism of the stomates have been observed.

To prevent leaf damage in tomatoes, the photoperiod is limited to 16 - 20 hours. Cucumber, sweet pepper, lettuce, begonia, chrysanthemum and *Ficus benjamina* can thrive under 24-hour photoperiods. Some rose cultivars can be lit for 24 hours, while others have a maximum photoperiod of 17-18 hours. If the photoperiod exceeds the maximum, the stomates remain open and transpiration continues, even during darkness. This may lead to severe reduction of vase life (Slootweg, 1991; Mortensen, 1999).

c. Age

The need for longer dark periods seems to increase with plant age, as has been determined for cucumbers.

d. Light use efficiency, LUE

Additional lighting at low intensities for prolonged periods may sometimes be more profitable than short periods at high intensities. The reverse may also be true. An 80% higher dry matter production was found when roses were supplemented for 24 h with 204 $\mu mol\ m^{-2}\ s^{-1}$ instead of 12 hours with 410 $\mu mol\ m^{-2}\ s^{-1}$ (Jiao, 1991). On the other hand, the growth of begonia, chrysanthemum, hedera, kalanchoe and pelargonium was better when supplemental lighting was provided over an 18-20 h photoperiod compared to a 24-hour photoperiod with the same light sum (Gislerød, 1989).

e. Light spectrum

Plants produce the same amount of dry matter whether the light source is sunlight or supplemental light. Still, differences may develop, but these relate more to stem elongation, development rate and leaf quality. The longer the lighting period, the greater these differences may become.

The lighting duration is thus limited by the light quality. Sunlight has a continuous and complete spectrum, while so-called assimilation lamps (*e.g.* HPS) have only a limited color spectrum. For this reason, certain plants show optimal growth at a given light sum of sunlight. But if the same light sum is supplied with assimilation lamps, disorders may develop, such as leaf drop, leaf curling, leaf chlorosis, necrosis and dieback. Whether and to what degree this happens depends on the type of lamp. For example, Mercury Metal Halide (MH) lamps (which contain more blue light), such as HQI-T (Osram) do not cause leaf necrosis in oriental lilies for certain photoperiods, while HPS lamps do. The development time under MH lamps is shorter than under HPS lamps, but with weaker flower stems and smaller buds (Bulb Research Centre, Lisse, The Netherlands). These negative effects can be reduced by growing at lower temperatures.

For chrysanthemums, the use of MH lamps resulted in lower net photosynthetic rates than under HPS lamps for short time intervals, but for longer time intervals the opposite was found. The reason can be found in the leaf aging effect. Leaf aging, which usually leads to reduction of photosynthesis, would occur more slowly under MH light compared to under HPS light (Walz et al., 1997). Therefore, the lamp type (light spectrum) should also be taken into consideration when lighting effects are being evaluated.

f. Light requirement of the crop

In Table 4.2, a classification of crops has been presented according to light requirements. This will be further discussed in Chapter 6. Many important horticultural crops have a high to very high light requirement. For these crops, it is economically prohibitive to use supplemental lighting to increase production to levels normally observed during the summer. For example, rose production and quality can be considerably improved and many problems with blind shoots avoided with an intensity of 100 μmol m^{-2} s^{-1} and long photoperiods.

Converting instantaneous light levels and light sums

*For **high-pressure sodium** (SON-T Plus 400 W) light:*

1 μmol $m^{-2}s^{-1}$ = 85 lux = 0.2 Wm^{-2} PAR = 7.9 ft-c (1)

For the conversion of lux to footcandle: 1 ft-c = 10.76 lux
For lux and ft-c as basis, the conversions are:
1,000 lux = 11.8 μmol m^{-2} s^{-1} = 2.4 W m^{-2} PAR = 92.9 ft-c
1,000 ft-c = 126.6 μmol m^{-2} s^{-1} = 25.3 W m^{-2} PAR = 10.76 klux

Measurements by the Research Station for Floriculture and Glasshouse Vegetables in Aalsmeer, show variations from 11.9 to 13.4 μmol m^{-2} s^{-1} per 1 klux.
The number of μmol m^{-2} s^{-1} per klux increases as the lamps get older and the lamp voltage is increased.

*For **daylight**, the following conversion can be used:*

1 μmol $m^{-2}s^{-1}$ = 56 lux = 0.217 Wm^{-2} PAR = 5.2 ft-c (2)

For lux and ft-c as basis, the conversions are:
1,000 lux = 17.9 μmol m^{-2} s^{-1} = 3.9 W m^{-2} PAR = 92.9 ft-c
1,000 ft-c = 192.3 μmol m^{-2} s^{-1} = 41.8 W m^{-2} PAR = 10.76 klux
The type of weather plays an important part in this conversion, see Table 5.2

Light sum using HPS
1 MJ m^{-2} PAR = 5 mol m^{-2} = 118 klxh = 10,970 ft-ch ***(3)***

Daylight sum *(45% PAR of total radiation)*
1 MJ m^{-2} PAR = 4.6 mol m^{-2} = 71.9 klxh = 6,640 ft-ch ***(4)***

On the other hand, for a crop like african violets, with a low light requirement, the summer production level can be reached using lower lighting intensities. Careful calculations will have to show whether this approach is profitable.

3. Shut-off times dictated by law

Some municipalities have enacted by-laws, which limit the light “emission” (“pollution”) from a greenhouse during certain periods of the day (*e.g.* between 20:00 and 24:00 hours in The Netherlands).

4. Technical factors

The lighting method may also depend on a number of technical factors. For example, the dark period can be applied section by section throughout the greenhouse operation. The lighting period then strongly depends on such a schedule. Or, when using moving supplemental lighting systems, the light sum will strongly depend on the speed with which the installation is moving.

4.2 Growth factors

Introduction

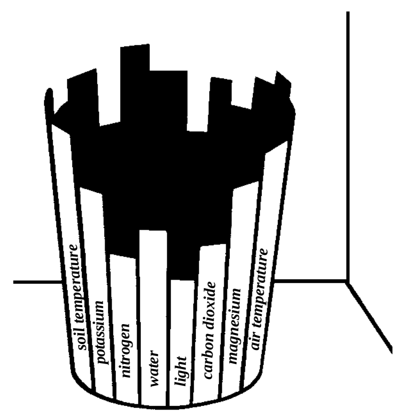
Some understanding of crop physiology is needed for greenhouse production. This knowledge serves as the foundation for environment control. The general aim is to adjust the growing factors to one another to obtain the optimal result with respect to yield and/or quality. Ultimately, the estimated economic result determines the production method. This is also true for supplemental lighting. Electric light is relatively expensive, but the benefits can be large as well.

> ***Growth factors:***
> - *Light*
> - *Carbon dioxide*
> - *Air temperature*
> - *Soil temperature*
> - *Relative humidity*
> - *Water / fertilizers*
>
> *The maximum growth rate depends on **the limiting factor,** which is frequently **light.***

Law of the limiting factor

This law (Liebig's Law) indicates that all growth factors should be properly adjusted to one another to obtain the highest possible yield. The growth factors can be presented as the uneven staves of a barrel. The contribution of each growth factor can be compared to the height of its stave (Figure 4.11). The shortest stave determines the maximum content of the barrel, or in other words, the maximum crop production. An example is given for tomato growth during December and February (Table 4.3). In December, the growth is severely limited due to the limited amount of light. Consequently, supplemental lighting will significantly increase plant growth. In February, there is sufficient light but a lack of water can inhibit growth. In the latter case, adequate irrigation will provide the greatest improvement. Only the most important production factors are mentioned here, but there are many more. The art of successful growing is to continuously improve the most limiting growth factor.

Figure 4.11. ***Law of the limiting factor.*** *In the same way a barrel cannot be filled higher than its shortest stave, a plant can not grow more than the most limiting growth factor allows.*



Light

Light is one of the most important growth factors, with intensity, duration, and spectrum playing an important role. This has been discussed in great detail in the preceding sections. During winter, light levels can be significantly reduced. Supplemental lighting during this period results in significant improvement of growth for crops with a dense canopy. During spring, this effect levels off, because the amount of natural light significantly increases. In assessing the benefit of lighting, the percentage of supplemental light as part of the amount of total light (supplemental plus sunlight) is important. The effects of small amounts of supplemental lighting are difficult to access. Nevertheless, the extra increase in dry matter production per quantity of extra supplemental lighting is more or less equal over a wide range of light intensities, as is the case between points A and B in Figure 4.12. This so-called linear relationship has been demonstrated for many crops, including begonia, fern, african violet, rose, and chrysanthemum. However, these crops exhibit large differences in light requirements.

growth factors	**mass** (g) **in December**	**mass** (g) **in February**
Sufficient water + high temperature + supplemental light	18	19
No supplemental light	7	16
No supplemental light + lower temperature	6	16
No supplemental light + lower temperature + insufficient water	5	11

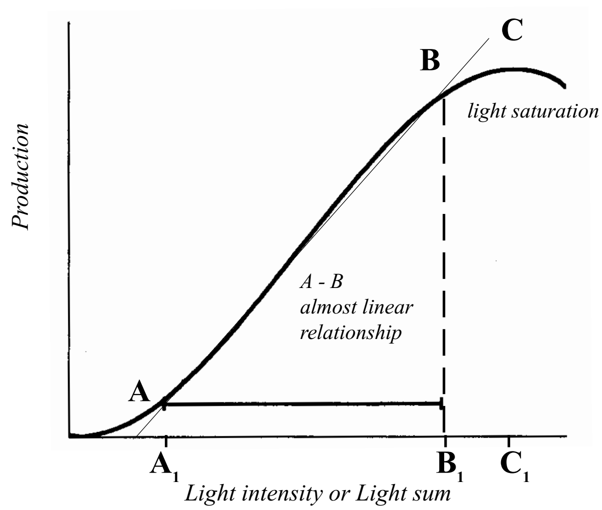
Table 4.3. ***Growth of tomato plants under different environment conditions***

In December, adding light provides the greatest benefit, while in February the effect of adequate water supply is greatest.

Figure 4.12. ***Production curve based on the incident light or light sum.***
This curve is used for lighting calculations to indicate the light requirement of crops.

*The production increases almost linearly between **A** and **B**. This means that the production increase per unit of light is constant. This assumption is valid for situations in which all other growth factors are optimized with respect to light.*

Source: D. Ludolph, 1995.



For rose (sun plant), the range of light intensity between point $\mathbf{A_1}$ to $\mathbf{B_1}$ (Figure 4.12) is much larger than for african violet (shade plant). For the range between points $\mathbf{B_1}$ to $\mathbf{C_1}$, light saturation is reached and the linear relationship is lost. The additional production per extra unit of light declines to zero in point **C** (= maximum). The range of light intensities over which this occurs may be wide or narrow. Supplying more light, for example, may lead to damage, and even result in production loss.

However, measured data often indicate that the production increase between points **A** and **B** is not quite linear. This is due to the fact that other growth factors are not optimal. The assumption in Figure 4.12 is that all other growth factors have been optimized in relation to the amount of incident light. Thus the law of the limiting growth factor applies. Besides environmental factors, other factors can inhibit optimal growth as well, *e.g.* inadequate plant density, excessive leaf area index, as well as plant age. Young leaves are more active than old ones, as was shown when rose stems were bent to increase production. To what degree a growth factor (*e.g.* the light sum) may be improved, depends on the costs and benefits. At the break-even point, the extra yield equals the extra costs. Under normal conditions, this point would be reached somewhere between points **A** and **B** (Figure 4.12). For example, the way in which heat from a total energy (co-generation) installation is used, affects the break-even point (Figure 6.1). The amount of heat generated through co-generation is strongly correlated with the amount of electrical (hydro) energy produced. If this heat cannot be utilized at the greenhouse operation, supplemental lighting soon becomes unprofitable. In addition to the purchase of a heat buffer, selling the surplus of heat may be a solution. An alternative option is installing a dual supplemental lighting system that can supply light with varying intensities, for example 35 and 70 $\mu mol\ m^{-2}\ s^{-1}$. When more heat is required, the light intensity is increased to 70 $\mu mol\ m^{-2}\ s^{-1}$. A useful approach to answering the question whether lighting is profitable is to express the additional biomass production per kilowatt hour (kWh, see Section 4.1).

Additionally, the most effective photoperiod should be determined for a given light sum. For roses, this is about 17-18 hours. For the rose cultivar 'Madelon' the same results were obtained when grown under a 16-hour photoperiod at 45 $\mu mol\ m^{-2}\ s^{-1}$ or under a 24-hour photoperiod at 30 $\mu mol\ m^{-2}\ s^{-1}$. The latter treatment is more cost-effective (see Section 4.1). Dark periods are often required for plants to unload starch produced and stored in leaves, because excessive accumulation may limit growth (*e.g.* rose). The change of the starch content in the leaves may help to determine the optimal photoperiod (Bakker, 1997a).

Carbon dioxide

Carbon dioxide is necessary for photosynthesis (Section 4.1). Increase of the concentration from ambient (350-400 ppm) to 800-1,000 ppm results in a production increase of 25-30% in most crops. In chrysanthemum, carbon dioxide enrichment raised the fresh and dry mass with 30 to 50% (Mortensen, 1987). Moreover, 10-20% more flowers developed with a 20-30% increase in cutting production and improved rooting. It is important to maintain the carbon dioxide concentration in a greenhouse during the light period above the ambient concentration. Particularly when the concentration drops below ambient, much potential production is lost. This tends to happen when the rate of photosynthesis is high.

During summer, the availability of carbon dioxide can be increased by slightly closing the ventilation windows in the afternoon when the sun is past its zenith (to preserve humidity). As a result, the temperature in the greenhouse will rise only slightly. By limiting the ventilation, the supplemental carbon dioxide remains in the greenhouse longer. When the concentration increases, the crop can absorb more carbon dioxide.

An increase of the carbon dioxide concentration can, to a certain extent, have the same effect as supplemental lighting, but it is a lot cheaper (Moe, 1976; Mortensen, 1983). As a consequence, supplemental lighting is only useful, when the CO_2 concentration is maintained at an optimal level. It is important to consider both supplemental lighting and CO_2 enrichment

when crop production needs to be increased. Key is to keep the carbon dioxide concentration adjusted to the temperature and light conditions (Figure 4.13). Through optimization, Heins et al. (1986) increased the dry matter production of chrysanthemums with 27% to 42%. At a given PPF, the optimum carbon dioxide concentration is represented by dashed line (OTC). The OTC-temperature curve represents the optimum temperature. In addition, the OT temperature line presents the optimum temperature at a given light level and an average carbon dioxide concentration of 330 ppm (ambient). For the OTC curve, the carbon dioxide concentration is optimized, for the OT curve it is not. The OT and OTC curves divert with increasing light intensity. The following example explains how to use Figure 4.13. At 230 μmol m^{-2} s^{-1} the optimum temperature according to the OT-curve is 17ºC, and according to the OTC curve 19ºC at 550 ppm CO_2. At approximately 500 μmol m^{-2} s^{-1} the temperatures are 21ºC and 26ºC, respectively, at 1,100 ppm of CO_2. This last condition is represented in Figure 4.13 with separate lines.
Higher light intensities and accompanying optimum growing conditions cause increased elongation, requiring more growth regulator to be applied.

Temperature

Temperature is the second most important environment parameter (after light). It affects many physiological processes such as photosynthesis, respiration, transpiration, uptake of nutrients, cell division, and cell elongation. Temperature manipulates a wide range of developmental processes from seed germination to flowering, from dormancy to development rate (cultivation period). Through environment control, the grower attempts to find an optimum growing environment, which, in view of the many separate processes, will often be a compromise. Furthermore, there is also a close correlation between temperature and relative humidity. Only a few aspects can be discussed here.

Light intensity/light sum and carbon dioxide

Carbon dioxide enrichment can replace 40% of the light requirement for mother plants of Campanula isophylla. Similar response was found for african violets. In general it is 30% for green plants; 40 to 50% for plants in the vegetative stage; and 20 to 30% for flowering plants and cut flowers (Moe, 1976).

Temperature affects:

1. The development rate

Development rate is affected by the daily average (24 hour) temperature. Cell division is stimulated by higher temperatures. Unfolding of flowers and leaves, and their subsequent development rates are higher. In this framework, the stimulating effect of high-pressure sodium (HPS) lamps on developmental rate can be explained. Experiments with vinca under HPS lamps indicated that the temperature of the shoot tips is increased by 1.2-1.7ºC at PPF of 50 and 75-100 μmol m^{-2} s^{-1}, respectively (Faust, 1997), compared to darkness. As the vapor pressure deficit increases, the plant temperature declined at most 1.2ºC, due to an increase of transpiration (Figure 4.14). In comparison with the air temperature, the plant temperature still remained 0.5ºC higher at the highest light intensity. In darkness, the temperature of the apical meristem is up to 1.5ºC lower than the air temperature at the highest vapor pressure deficit (3 kPa). If supplemental lighting is applied during the daytime when little sunlight is available, the plant temperature is usually 2ºC higher compared to plants without supplemental lighting.

Light intensity/light sum and carbon dioxide
Carbon dioxide enrichment can replace 40% of the light requirement for mother plants of *Campanula isophylla*. Similar response was found for african violets. In general it is 30% for green plants; 40 to 50% for plants in the vegetative stage; and 20 to 30% for flowering plants and cut flowers (Moe, 1976).

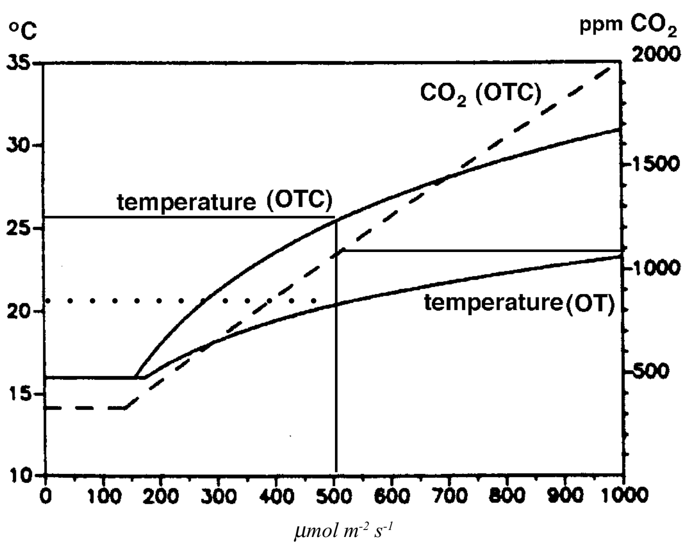
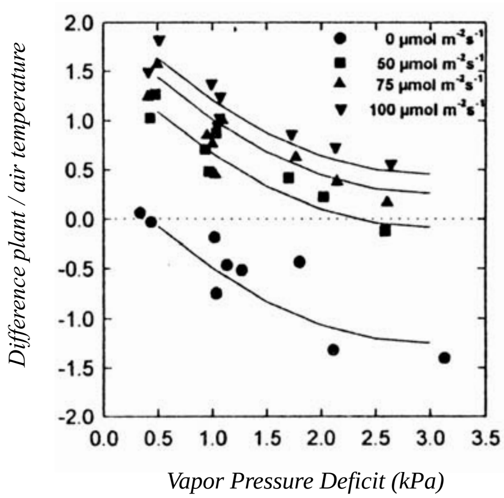


Figure 4.13. ***Mutual adjustment of temperature and CO_2 concentration to light intensity with chrysanthemum.***
*The **OT temperature** line represents the optimal temperature at a given light level and a CO_2 concentration of 330 ppm.*

*The dashed line, CO_2 (**OTC**) represents the relationship between the predicted CO_2 concentration and light intensity destined for the OTC environment.*

*The **OTC temperature** curve represents the optimal temperature at a certain light level, when the CO_2 concentration is optimized according to the CO_2 curve (OTC).*
Source: Heins et al., 1986.
(Reprinted with permission of Amer.Soc.Hort.Sci.)

Figure 4.14. ***Effect of Vapour Pressure Deficit at different light intensities on the difference between plant and air temperature of Vinca*** *(Catharanthus roseus).*
Source: Faust en Heins, 1997.
(Reprinted with permission from ISHS.)



Relationship between Relative Humidity (RH) and Vapor Pressure Deficit (VPD)

Vapor Pressure Deficit (VPD) is expressed in kPa and is dependent on temperature.
The table below holds at 18°C.

0.1 kPa VPD	~	*95% RH*
0.4 kPa VPD	~	*80% RH*
0.7 kPa VPD	~	*65% RH*
1.1 kPa VPD	~	*50% RH*

The relationship between development rate and daily average temperature is often linear over a range from base to optimum temperature. This means that in this range a higher daily average temperature result in a shorter production time (Roberts, 1987).

At temperatures below the base temperature, the time till flowering becomes infinite, while temperatures above the optimum are detrimental to the development and may delay flowering. For *Lilium longiflorum,* a 1.5°C higher plant temperature at an air temperature of 15°C results in a 10% faster development (*e.g.* leaf unfolding rate). The higher the minimum or base temperature for crop growth, the larger this effect is. For example, the base temperature is 9.8°C for hibiscus, 5.6°C for poinsettia, and 1.2°C for *Lilium longiflorum*. At an air temperature of 15°C the production time for these crops declines with 23, 14 and 10%, respectively, relative to crops grown at the base temperature (Faust, 1997).

2. **Stem elongation**

The difference between day and night temperature (DIF) in many crops affects the amount of stem elongation. For positive DIF (higher day than night temperature): the greater the difference becomes, the taller the plant. Negative DIF (lower day than night temperature) inhibits internode length, and by closing the energy screen at night, energy savings can be realized (*e.g.* chrysanthemum).

3. **Dry matter distribution**

The growth of separate parts of the plant can be manipulated through temperature modification. Higher air temperatures promote the ‘sink’ effect of aerial growing tips, at the expense of the roots (a ‘sink’ attracts nutrients and sugars). Roots, which receive higher temperatures likewise attract more sugars, so that their growth is stimulated. This may be at the expense of the aerial growth. For roses, increasing the root temperature from 17 to 21°C results in extra consumption of sugars. The positive effect of supplemental lighting on the aerial growth is then greatly diminished (Bakker et al., 1997). Aerial and soil/substrate temperatures should be accurately controlled.

4. **Dry matter accumulation**

Sometimes, growth rates need to be increased. This may be achieved with a higher daily average temperature. In such case, it is important to determine whether this is at the expense of dry matter accumulation. The respiration, which takes place during day and night, will then consume more sugars, which results in a reduced dry matter accumulation. The more vegetative growth, the more significant the sugar consumption, particularly during periods when light becomes the limiting factor. Therefore, either the leaf area or the temperature should be adjusted. During winter, small thin-walled cells develop at high temperatures and thicker cell walls at lower temperatures. This is caused by the availability of assimilates (sugars) per cell formed. When, in addition, the irrigation is limited, even during winter, a strong crop develops with tough cells. Fresh mass production will be reduced.

Relative humidity (RH)

In general, plant growth decreases with a lower relative humidity, while the crop gets lusher as RH increases. The combination of high RH and low light intensity generally promotes stem elongation and leaf expansion.

Due to the fact that greenhouses become more airtight and energy screens are used more frequently, the relative humidity of the greenhouse air during the crop cycle has increased. In general, a RH between 55 and 90% appears to have little harmful effects on the physiology of horticultural crops (Hand et al. 1996). On the other hand, when crops are grown for a prolonged period of time at a RH of 90% or higher, problems can be expected with growth and development (Grange, 1987). Well-known examples are deficiency symptoms as a result of low calcium supply to young, fast growing plant parts (blossom-end rot in tomato, tipburn in lettuce).

Next, several well-documented cases of crop responses to certain RH conditions are described. For chrysanthemum, the effects are somewhat contradictory. If the RH is raised from 55 to 95% during long-day, dry matter production and stem length increase. Due to the greater leaf area, the plant is able to build up more sugars through photosynthesis (Mortensen, 1986). These RH effects have been confirmed later under short-day conditions by Gislerod (1989). The increased growth was believed to be the result of a higher carbon dioxide uptake, because the stomates opened wider during high humidity conditions. British research, on the other hand, found a small decrease of the total leaf area and the leaf dry mass at a high RH (to 95%). It was found that the production time to flowering was prolonged with 4 to 5 days. Under normal greenhouse conditions, however, very high humidities rarely occur over a long period of time. The conclusion can be drawn that chrysanthemum has a relatively low sensitivity to high relative humidity conditions (Hand, 1996).

Increasing the RH from 50 to 85% improves the growth of lettuce (Tibbitts, 1976), while for pot plants an increase in RH from 40 to 65% has a similar effect (Krizek, 1971).

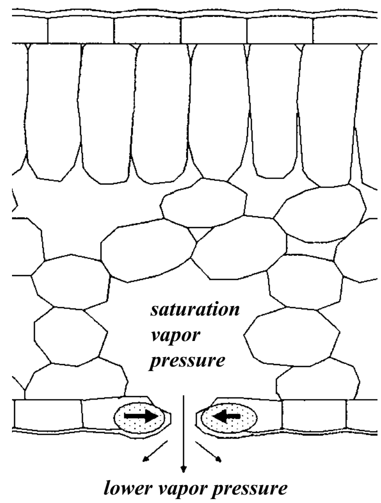
Recent experiments demonstrated adverse effects of high RH on the vase life quality of roses (Mortensen, 1999), particularly in combination with continuous lighting (Table 4.4). When the RH was increased from 83 to 91%, the shoot fresh mass dropped 11% (on average for 14 cultivars). The vase life declined with 12 to 75%, when the RH was increased from 75 to 91% at a photoperiod of 18 hours. When this period was extended to 24 hours, the keeping quality of those cultivars declined 31 to 78%, primarily due to water loss in the leaves.

Table 4.4. ***Vase life (in days) of roses grown at different RH and photoperiod (PP).***

Source: Mortensen, 1999.

PP		***18 h***	
RH %	***75***	***83***	***91***
Amadeus	*11.3*	*10.5*	*5.8*
First Red	*11.7*	*10.4*	*9.3*
Frisco	*16.3*	*15.7*	*14.1*
Golden Gate	*15.4*	*15.4*	*12.8*
Prophyta	*15.0*	*11.7*	*7.1*
Sacha	*12.8*	*11.5*	*8.2*
PP		***24 h***	
RH %	***75***	***83***	***91***
Amadeus	*7.6*	*3.6*	*1.7*
First Red	*10.5*	*7.8*	*4.7*
Frisco	*15.4*	*13.2*	*10.7*
Golden Gate	*14.7*	*12.0*	*9.9*
Prophyta	*8.4*	*7.2*	*4.4*
Sacha	*9.0*	*5.0*	*4.5*

Figure 4.15. ***Transpiration through leaf stomates.***



The relatve humidity in the stomatal cavity is considered to be 100% (saturated air with the so-called saturation vapor pressure). The saturation vapor pressure increases with temperature. The rate of transpiration depends on the vapor pressure deficit between air in the stomatal cavity and the surrounding air as well as the stomatal resistance.

Source: Timmerman, 1990.

Transpiration

Leaf transpiration declines with increasing RH of the surrounding air, while it increases with declining RH. The vapor pressure deficit between the air inside and outside the stomates is the driving force for plant transpiration. The degree of transpiration is determined by the degree of opening of the stomates (Figure 4.15). When water supply cannot keep up with transpiration, the stomates close to protect the plant against excessive water loss. This can also occur when the RH in the air drops suddenly (*e.g.* leaf burn during lily production). Stomates also start to close due to high carbon dioxide concentrations, high leaf temperatures, leaf senescence and/or air pollution.

Early in the morning, stomates open due to increased turgor pressure in their guard cells as a result of the start of photosynthesis. Thus, the stomatal resistance is reduced and transpiration occurs. A fast growing crop needs adequate transpiration, as well as sufficient water uptake by the roots. The transpiration flow allows absorbed nutrients and hormones to travel from the root tips and to be distributed throughout the plant. The result is a strong root system and good cell and plant development. The opposite occurs when plants have inadequate transpiration due to a high RH in combination with a high soil temperature. For example, due to active water uptake by the roots, water can be forced between cells, and a disorder such as glassiness (water-soaked appearance) may develop.

Transpiration provides cooling of the leaves. If there is insufficient cooling, leaves can become stressed. In full sun, the leaf temperature can increase more

Effect of leaf temperature on transpiration

An example with an air temperature of 20°C and a Relative Humidity of 80% is described. This leads to a vapor pressure of 1.8 kPa. At a relative humidity of 100% and 20°C in the stomatal cavity, the vapor pressure is 2.4 kPa.
The vapor pressure deficit is thus:

2.4 – 1.8 = 0.6 kPa (I)

If the leaf temperature is 2°C higher than the air temperature due to HPS lighting, the vapor pressure in the leaf becomes 2.7 kPa.
The vapor pressure deficit between the greenhouse air and the stomatal cavity is now:

2.7 – 1.8 = 0.9 kPa (II)

This change results in an increase in the vapor pressure deficit of 0.3 kPa

Therefore, the transpiration rate should be higher in case II (assuming the stomatal resistance remains the same). However, research showed this is not the case. From the increase in leaf temperature it may be concluded that the cooling capacity from the increased transpiration is not able to keep up with the incident radiation. Faust and Heins (1997) hypothesized that stomatal resistance increases under supplemental lighting. This hypothesis requires further study.

than 10°C above air temperature. Dry soil, high salt concentrations, small root system and low soil temperature are some of the possible causes of limited water uptake, which lead to water stress in aerial plant parts.

Effect of carbon dioxide concentration
Stomates close in response to an increase in carbon dioxide concentration in the air. In tomato, sweet pepper, and cucumber crops, stomates are estimated to close 3% for every additional 100 ppm CO_2, while egg plant shows a three times stronger response (Nederhoff, 1992). If the CO_2 concentration increases to 700 ppm, the transpiration in the former three crops is only 10% reduced (stomates are approximately 40% closed) compared to ambient CO_2. Similarly, in egg plant, there is a 20% reduction in transpiration which causes the leaf temperature to rise approximately 1°C.

Effect of the sunlight and HPS light
Under natural sunlight the stomata probably open more than under HPS light. This can result in a larger difference between plant and air temperature under supplemental lighting due to the reduced transpiration. When the lamps remain off during the day, the leaf temperature is usually slightly below air temperature. As soon as the lamps are switched on, the leaf temperature increases with almost 2°C depending on the RH and the light intensity (Faust, 1997).

Effects of the spectra of sunlight and HPS light
The composition and energy distribution of HPS light is thought to be the cause of a reduction in stomatal opening. Sunlight contains much more blue light compared to HPS light. It has been demonstrated that, in addition to red light, the opening of stomates is also stimulated by blue light (Schwarz and Zeiger, 1984). When sunlight is combined with HPS light, the leaf temperature is always higher compared with sunlight alone. This would imply that the blue portion of sunlight did not adequately compensate for the different color spectrum of HPS light. The blue light explanation is therefore not the only reason. An alternative explanation may be found in the different energy distributions of sunlight and HPS light (Faust, 1997).
According to Faust, for HPS light, each increase in watt in the range 400-700 nm (PAR) results in an extra 1.76 watt energy in the range of 700 to 50,000 nm, while for sunlight this is only 1.18 watt. In fact, there is little solar radiation past 2,800 nm and plants absorb little energy between 700 and 2,800 nm (Figure 3.1). However, HPS light consists for approximately 45% of radiant energy with wavelengths between 2,800 and 100,000 nm, which plants absorb almost completely (Figure 4.16).
In terms radiant energy and for a light intensity of 100 µmol m^{-2} s^{-1}, this is 45% of 74 W m^{-2} or 33 W m^{-2} (Bubenheim, 1988). This latter value is significant. A temperature rise of the leaf is thus possible. Due to the higher leaf temperature the vapor pressure deficit between the air inside stomatal cavities and surrounding air increases. The transpiration, and consequently the cooling should therefore increase also.
However, this does not happen adequately. The explanation has to be found in the factors affecting stomatal opening.
For high-pressure sodium lamps, around 70% of the electricity supplied to a 400 watt lamp, is converted

Radiant energy distribution of HPS-lamps

Per µmol m^{-2} s^{-1} light in the wavelength area between 400 and 700 nm, the total radiant energy is:
0.74 W m^{-2} (300-100,000 nm).
At an intensity of 400 µmol m^{-2} s^{-1} the radiant energy is 296 W m^{-2}, which can be further divided into the following wavelengths (Bubenheim, 1988).

27% in 400 - 700 nm PAR
28% in 700 - 2,800 nm NIR
45% in 2,800 -100,000 nm FIR

NIR = near-infrared radiation
FIR = far-infrared radiation

Note the energy between 300-400 nm is negligible (0.8%).

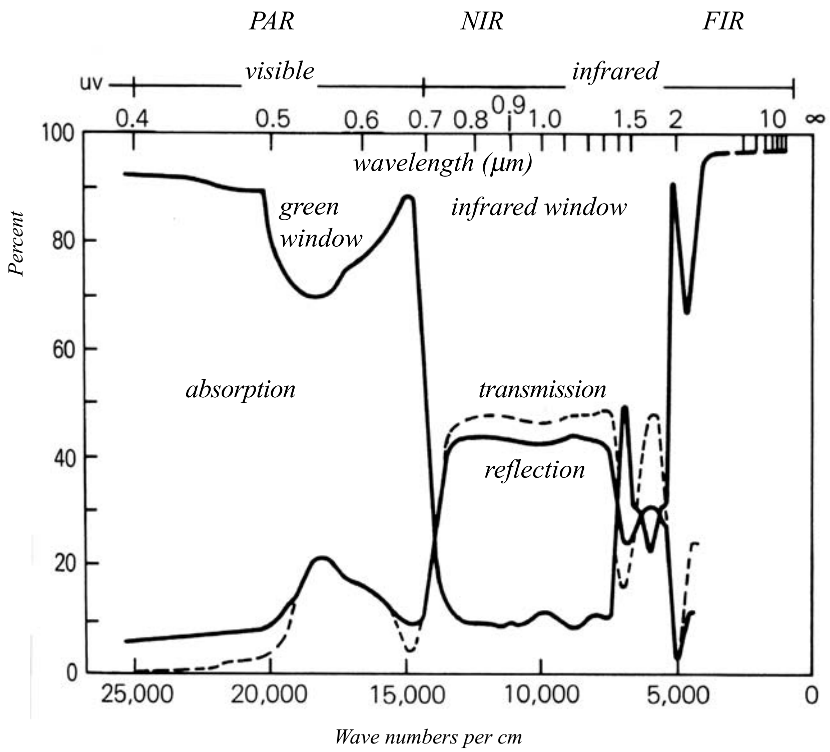


***Figure 4.16:* Absorption, transmission and reflection of radiation by a leaf** *(Mimulus cardinalis).*

Note the "windows" in the green and near-infrared (NIR or IR-A and B) wavebands, in which absorption is considerably reduced. However, radiation in the far-infrared area (FIR or IR-C) with wavelengths of more than 3,000 nm (3 mm) are absorbed completely by the leaf. Precisely in this area, the HPS lamp produces a large part of its radiant energy (see related text box).

Source: Gates et al., 1965.

(Reprinted with permission from The Optical Society of America.)

into heat radiation (Figure 4.17). The remaining 30% becomes PAR light of which only 1 to 2% is effectively utilized in the photosynthesis. The major part of the PAR radiation (28-29%) is thus also converted in the leaf into heat radiation. In all, about 92% of the supplied electricity is converted into sensible heat (Tantau, 1997). A very large proportion is lost to transpiration both by the plant and by wet surfaces. If, for example, 460 watt is supplied to a light fixture with a HPS lamp of 400 W, 50-60% (approximately 250 watt) would be used for transpiration, as a low estimate. In temperate climates the evaporation is 60-80% from a free water surface (Doorenbos et al., 1984).

After lighting for 2.7 h one fixture can cause an extra transpiration of 1 L (or 1 kg) of water. For the evaporation of 1 L of water a considerable amount of energy is required which helps to cool the plant (between 2.4-2.5 MJ kg^{-1}, Salisbury, 1992, p.82).

It is obvious that, if supplemental lighting occurs under energy curtains, the RH increases. To avoid this, an opening of the curtain during the night is recommended. In addition, extra irrigation should be provided for long lighting periods.

Water / fertilizers

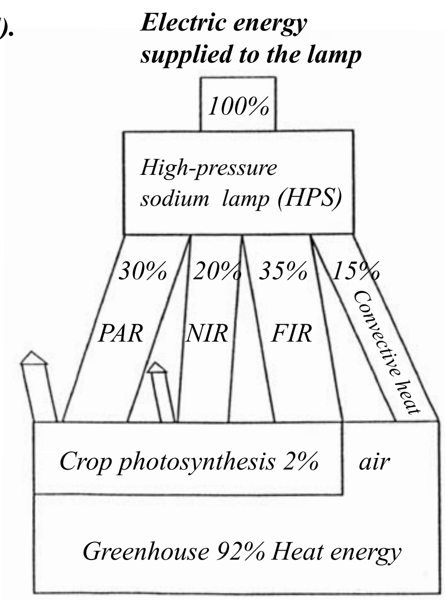
It has been demonstrated that water uptake may be a limiting factor for growth (Table 4.3). This is also true for nutrients. To obtain the highest profit from supplemental lighting, these important growth factors should be managed well.

Water is necessary for photosynthesis (1%). About

***Figure 4.17.* Energy fluxes for a high-pressure sodium lamp (HPS).**
Source: Tantau, 1997.

(electric energy = 100%).
400 - 700 nm PAR
700 - 2,800 nm NIR
2,800 -100,000 nm FIR

PAR = photosynthetically active radiation
NIR = near-infrared radiation
FIR = far-infrared radiation



90% of the water taken up by roots is lost through transpiration, depending on growth and development. Water functions as a means to transport nutrients and hormones. About 10% remains behind in the plant. Water is used by cells to maintain turgor and for the growth of new cells. If water uptake is limited during growth and development, plants remain more compact (bedding plants), but fresh yield may decline. In tomato production, for example, water uptake can be manipulated by adjusting the salt concentration (EC) in the nutrient solution. The fruits become smaller, but flavor improves. In general, water uptake depends on water and nutrient supply, and on the salt concentration in soil or substrate. The uptake is closely related to consumption. With the exception of succulents and cacti, water consumption of plants is for a major part determined by the light sum. If the photoperiod is extended to 20 or 24 hour with supplemental lighting, the crop consumes more water. Water stress should be avoided, because this causes closure of stomates, and, thus, less CO_2 is taken up by the leaves and photosynthesis decreases.

Water and nutrient supply are controlled easier and more quickly in crops grown in substrates compared to soil-grown crops. Regular checks of salt concentration, pH, and nutrient composition are required. The growing conditions in substrates can usually be controlled more easily compared to in soil, partly because substrate temperature is usually closer to air temperature. The uptake of some nutrients is an active process requiring energy. This energy is supplied through respiration. For this, oxygen and a sufficiently high temperature are needed. Therefore, a yield increase of 20% for crops grown in substrates in substrate crops is possible, compared to soil grown crops.

Specific fertilization schemes make it possible to manipulate the vegetative (nitrogen) and generative (potassium) growth or height of bedding plants. Elongation may be controlled by an increase in EC as well as limiting the phosphate nutrition. Insufficient light causes an accumulation of nitrate in the leaves of a number of leafy crops (*e.g.* lettuce). Supplemental lighting may help to produce sufficient carbohydrates to incorporate the excess nitrogen.

5 *Lighting Units and Conversions*

5.1 Units and concepts

Depending on the application, different units of measurement are used for light intensity: radiometric, photometric and quantum units of measurement.

5.1.1 Radiometric units

Preferred units: *watt and joule* (Langleys, Calories, and BTU are outdated).

These units express the incident radiant energy per unit surface area per unit of time. For supplemental lighting purposes, it is important to know how much of the radiant energy supplied by a light source is converted into radiation useful for growth and development of plants. In addition, energy distribution over the color spectrum is an important parameter because energy content varies with wavelength. *Photosynthetically Active Radiation (PAR)*, between 400 and 700 nm, is defined as the quantity of light available for photosynthesis. Photoperiodic lighting requires light with a wavelength between 280 and 800 nm.

Pyranometers (Figure 3.4), which can be used to measure the so-called global or total radiation from the sun, measure light with wavelengths between 280 and 2,800 nm. On average, only 45% of the global radiation (varying within a range of 40 to 59%, depending on cloudiness and time of the day) is PAR. The conventional units for expressing PAR are $\mu mol\ m^{-2}\ s^{-1}$, but PAR can also be expressed in $watt\ m^{-2}$, and, in that case, with a specific explanation indicating only the radiant energy in the PAR waveband is included $(watt\ m^{-2}\ PAR)$. One of the shortcomings of using $watt\ m^{-2}\ PAR$ is that the different light colors are treated similarly. $Watt\ m^{-2}$ *of PAR* expresses an energy flux, rather than a flux of photons, which corresponds more appropriately with the potential photosynthetic activity. As a result, different conversion factors exist for different light sources when converting the numbers of *photons* m^{-2} *into* $W\ m^{-2}$ *of PAR*. For example, for daylight under a sunny, blue sky, a conversion factor of 4.6 $\mu mol\ m^{-2}\ s^{-1}$ *per* $W\ m^{-2}$ *of PAR* is used, but for the light from a high-pressure sodium lamp this factor is 5 $\mu mol\ m^{-2}\ s^{-1}$ (a difference of 8%).

Definitions:

The unit of power ***watt*** (with symbol ***W***) expresses an power quantity and can be used to indicate light as well as mechanical or electrical power.

One *watt* is equal to one *joule* of work in one second $(1\ W = 1\ J\ s^{-1})$. An equivalent is the power dissipated in an electrical conductor carrying a direct current (DC) of one *ampere (A)* between two points at one *volt (V)* potential difference.

The symbol *kW (kilowatt)* is used to indicate the energy delivering capacity of a generator, motor, electric heater or a lamp *(1 kW = 1,000 watt)*.

Furthermore, *kilowatt-hour (kWh)* can be used as a unit for light sum or for amount of energy delivered:

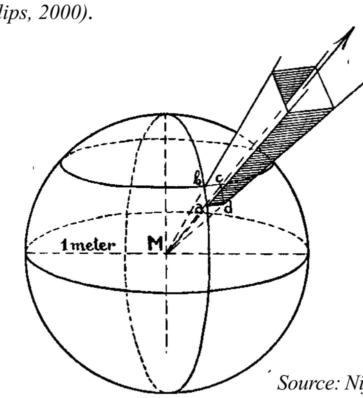
$$1\ kWh = 1{,}000\ watt \times 3600\ seconds = 3.6 \cdot 10^6\ joule = 3.6\ MJ.$$

The unit of work or energy ***joule*** (with symbol ***J***) is equal to the work done by a force of one newton acting through one meter $(1\ J = 1\ Nm = 1\ kg \cdot m^2\ s^{-2})$. The unit ***joule*** also expresses the energy released in one second by a current of one ampere through a resistance of one ohm. With lighting, joule expresses a quantity of energy of one watt for one second, according to the definition: $1\ J = 1\ W\ s$. The radiant energy flux from the sun or lamp received on a unit plane surface is frequently expressed as $J\ cm^{-2}$ or $J\ m^{-2}$ per unit of time (*e.g.* hours or days), called light sum.

Figure 5.1. ***Definition of luminous flux (lumen).***

*In the centre of a sphere, a light source **M** radiating with an intensity of 1 candela emits a luminous flux of 1 lumen through an area of 1 m^2 of the sphere's surface (abcd). The sphere has a radius (r) of 1 m and a total surface area of 12.57 m^2 ($4\pi \cdot r^2$). Therefore, the light source **M** provides a total luminous flux of 12.57 lumen.*

An incandescent lamp of 150 W-Superlux is rated at 2,060 lumen, a 400 W-SON-T Plus lamp at 55,000 lumen and 600 W-SON-T Plus lamp at 90,000 lumen (Philips, 2000).



Source: Nijhoff, 1969.

Candela

Is defined as the luminous intensity, in a given direction, of a source that emits monochromatic radiation at a frequency of $540 \cdot 10^{12}$ Hz and that has a radiant intensity in that direction of 1/683 W per steradian.

5.1.2 Photometric units

Lumen, lux, and foot-candle (1 lux = 1 lumen m^{-2}).
These are units of illumination in the visible waveband (380 – 770 nm).

Lumen *(lm)* is defined as the luminous flux through 1 m^{-2} of a sphere's surface, with a radius of 1 m around a light source with a luminous intensity of one *candela*. Such a light source of one *candela (cd)* provides a luminous flux of 12.57 *lumen* with an energy content of 1.89•10^{-2} J s^{-1}. Therefore, a luminous flux of 1 *lumen* through a surface of 1 m^{-2} corresponds to energy content of 15•10^{-4} J s^{-1}. See also Figure 5.1.

Lux *(*with symbol *lx)* is a measure of illuminance. One *lux* (Latin for "light") is the amount of illumination provided when one *lumen* is evenly distributed over an area of 1 m^2 of a sphere's surface.

1 lux = 1 lumen m^{-2} = 1 cd•sr m^{-2},(sr = steradian).

Foot-candle *(ft-c)* is a measure of illumination and similar to *lux* with a feet as standard in stead of a meter. One *foot-candle* is the amount of illumination provided when one *lumen* is evenly distributed over an area of 1 ft^2 (= 0.0929 m^2) of a sphere's surface, with a radius of 1 ft (0.3048 m) around a light source with an intensity of one *candela*.

Therefore, *1 lux = 0.0929 ft-c*, and *1 ft-c = 10.76 lux.*

The units *lumen, lux* and *foot-candle* are based on the sensitivity of the human eye, which peaks around 555 nm (Figure 3.13), while plant sensitivity is highest in red at 700 nm. Therefore, using *lumen, lux* and *foot-candle* as units to express the quantity of light available for photosynthesis is less appropriate, especially when the type of light source is not considered. For example, the effect of high-pressure sodium light on the rate of photosynthesis is overestimated by approximately 50% compared with sunlight when both light intensities were initially expressed in equal amounts of *lux*. Lux meters are calibrated from incandescent lamps having a color temperature of 2850 K, which means that an error is produced whenever light is measured from lamps at a different color temperature.

5.1.3 Quantum units

PPF (***Photosynthetic Photon Flux)*** or ***PAR (Photosynthetically Active Radiation)*** are used to express the number of photons in the waveband between 400-700 nm reaching a unit area per unit time. PPF is usually expressed in μmol m^{-2} s^{-1}; in micromole because small quantities are concerned (μmol = 10^{-6} mol). The symbol *mu* (μ) is used to indicate "micro". In the case of light sums (*e.g.* to express the daily solar radiation), the unit mol m^{-2} d^{-1} is frequently used. The correlation between photosynthesis and PPF is better than that between photosynthesis and radiometric *(W m^{-2})* or photometric units *(lux)*. Consequently, the PPF unit is preferred by plant physiologists.

The highest light intensity (PPF) of sun light inside a greenhouse is approximately 1,400 μmol m^{-2} s^{-1} in The Netherlands and North America.

The adaily light sum inside a grrenhouse varies between 1 and 35 in mol m^{-2} (Bakker, 1997b). For monthly averages, see Table 5.3.

5.2 Daylight

Each week, the Research Station for Floriculture and Greenhouse Vegetables (PBG) publishes daily light sums (global radiation) for Naaldwijk, The Netherlands. The data are presented in units of joule cm^{-2} d^{-1}. Total radiation, heating strategy, use of supplemental lighting, and crop stage, determine for a large part the transpiration of greenhouse crops. A correlation exists between total incoming radiation and crop water use. In some cases up to 70% of the total incoming radiation is used for evaporation. Due to changing solar elevation, reflection, and atmospheric conditions, approximately 70% of the outside solar radiation is transmitted through a new and glass-clad greenhouse structure. Of the outside solar radiation, approximately 45% is PAR. For example, when for a particular day the outside global radiation is 1500 J cm^{-2} d^{-1}, this results in an inside radiation level of

0.7 x 0.45 x 1500 J cm^{-2} d^{-1} =
473 J cm^{-2} d^{-1} PAR (= 21.8 mol m^{-2} d^{-1}).

5.3 Conversion of light units

Conversion of light units is frequently necessary to compare measurements taken with different instruments. Several useful conversion factors are shown in Table 5.2. However, conversions should be performed carefully with understanding of the original measurement technique and the light source involved in order to reduce errors. For measuring total short wave radiation (280–2,800 nm), a pyranometer is preferred, for photosynthesis (400–700 nm) a quantum sensor, and for visible light (380–770 nm) a lux meter (Van Rijssel, 1999). The conversion of daylight can cause errors due to solar elevation and sky cloudiness (Table 5.1). When the sun has a low elevation angle, the amount of ultraviolet and visible light declines rela-

Table 5.1. ***The composition of solar radiation.*** *Source: CIE, 1989.*

Solar elevation	Cloudiness *%*	Total Radiation *W m^{-2}*	percentage Ultraviolet *300-400 nm*	percentage PAR *400-700 nm*	percentage Infrared >700 nm
40	0	680.7	5.9	45.2	48.9
10	0	52.9	5.4	42.8	51.8
40	3	595.2	6.1	47.2	46.7
40	10	387.9	7.2	51.5	41.3
40	30	200.5	8.3	54.2	37.5
40	100	69.2	9.8	59.3	30.9

Table 5.2. ***Conversion factors between radiometric (watt m^{-2}), quantum flux (µmol m^{-2} s^{-1}) and photometric units (lux).*** *Sources: PBG (1996), Thimijan and Heins (1983)*, Fisher and Faust (2001)** and manufacturers.*

1	2	3	4	5
Light Source	**watt m^{-2} PAR per watt m^{-2} global**	**µmol m^{-2} s^{-1} PPF per watt m^{-2} PAR**	**lux per µmol m^{-2} s^{-1}**	**lux per watt m^{-2} PAR**
Daylight average	0.45	4.6	56	258
Daylight, sun and sky*	0.45	4.6	54	247
Daylight, sky*	0.45	4.2	52	220
Daylight**	0.43	4.7	54	250
Daylight, cloudy	0.46-0.53	4.2	56	256
Incandescent 150 W-Philips	0.064-0.076	5.1	49	250
Incandescent*	0.07	5.0	50	250
TL 33, fluorescent lamp, Philips		4.6	78	355
Fluorescent Warm White*		4.7	76	355
Fluorescent Cool White*		4.6	74	340
SON-T 400 W, HPS, Philips	0.35	4.9	83	410
SON-T agro 400 W, HPS, Philips	0.39	4.9	84	413
HPS 400 W**	0.35	5.0	83	414
SON-T plus 400 W, HPS, Philips	**0.39**	**5.0**	**85**	**425**
HPI-T 400 W, MH lamp, Philips	0.36	4.5	83	377
MH 400 W**	0.37	4.6	72	326
Lumalux 400 W, HPS, Osram Sylvania		4.9	85	413
HQI-T 400 W, MMH lamp, Osram		4.5	65	290
NAV-T Super, 400 W, HPS, Osram		5.0	72	356

tively significantly. As being highly absorbed by water (vapour), the percentage of infrared radiation declines under cloudy conditions.

Table 5.2 explained

Column 2 of Table 5.2 shows that, on average, 45% of solar radiation is PAR (400 - 700 nm). This conversion factor ranges between 0.45 and 0.53 for sunny and overcast conditions, respectively. For high-pressure sodium light, this conversion factor is significantly lower: 0.39. Therefore, for HPS light, only 39% of the global radiation emitted (280 - 2,800 nm) falls in the PAR waveband and can be used for photosynthesis. The conversion efficiency per watt of electric energy supplied is even lower because HPS lamps emit a relatively large amount of heat radiation (Figure 4.17).

According to Figure 3.6 human eye sensitivity to light is outside 400-700 nm almost zero, lux is considered as PAR light. Therefore, no adjustment is made to lux when converted to watt or micromole, (compare global radiation and PAR-radiation).

Table 5.2 by column:

The first column indicates the light source. The second column shows the percentage of PAR radiation (400 – 700 nm) as part of the global radiation (280 – 2,800 nm). The third column shows the conversion factor for PAR from µmol m^{-2} s^{-1} to W m^{-2}. For example, when HPS lamps are used, 100 W m^{-2} PAR can be converted into 100 x 5 = 500 µmol m^{-2} s^{-1}. Similarly, in column 4, the conversion factor is shown from lux into µmol m^{-2} s^{-1} PPF. An HPS lamp produces 85 lux for every µmol m^{-2} s^{-1} of PAR. Using the conversion factors in column 5, the light intensity in lux can be converted into W m^{-2} PAR. For HPS lamps, 425 lux corresponds with 1 W m^{-2} of PAR.

Comparing lamp light and sunlight

Supplemental light from HPS (SON-T Plus) lamps with a PPF of 75 µmol m^{-2} s^{-1} can be converted into 6,375 lux (75 x 85). For average sunlight, this conversion is (according to column 4) 75 x 56 = 4,200 lux.

Sunlight with an intensity of 75 µmol m^{-2} s^{-1} can be converted into 75/4.6 = 16.3 W m^{-2} PAR (Column 3). For HPS is this 75/5 = 15 W m^{-2} PAR.

Light sum

The duration of the light period multiplied with the average light intensity results in the light sum (or light integral). This light sum is an important parameter determining plant production. Some calculations involving light sums are shown in Table 5.3.

Light intensity (and, thus, light sums) can be determined with various instruments and expressed in different units. For example:

1. Lux meter (Figure 5.2)

A lux meter is used to measure the instantaneous luminous intensity in the visible waveband (380–770 nm). For example, if the average hourly light readings for a particular 8-hour daylength (in klux) are:
2, 4, 3, 6, 5, 4, 2, 1, then the daily light sum is:
27 kilolux-hour (or 27 kluxh d^{-1}).

Figure 5.2. ***Lux meter.***
In general photometers measure the level of illumination in the waveband between 380 and 770 nm. The meter shown, HD 8366, uses a silicon sensor and measures in the range from 0,1 to 200,000 lux and from 400 to 760 nm. Source: Brinkman, B.V., Delta Ohm SRL.

2. Pyranometer (Figure 5.3)
A radiometer is used to measure the irradiance on a plane surface (in W m^{-2}), resulting from radiant fluxes in the waveband between 280 and 2,800 nm. Consequently the light sum can be expressed in Joule per cm^{-2} (or J cm^{-2}), because 1 W = 1 J s^{-1}. For example, if for each successive second the measurements (W m^{-2}) are: 46, 60, 51, 58, 63, there the radiation sum will be 278 J m^{-2}. To avoid large numbers, these radiation sums are usually expressed in Joule per cm^{-2}: 278/ 10,000 = 0.0278 J cm^{-2}. The light sum can also be expressed in watt-hour (Wh) per m^2, requiring the light intensity in W m^{-2} and the duration of the light period (hr). For example, in January for Naaldwijk, The Netherlands, in a greenhouse with average light transmissivity of 60%, the average light intensity is 22 W m^{-2} (PAR) and the daylength is 8 hours (Table 5.3). This results in a light sum in the greenhouse of 8 x 22 = 176 Wh m^{-2} d^{-1}.

3. Quantum sensor (Figure 5.4)
A quantum sensor measures the instantaneous photon flux density in the PAR waveband (400-700 nm) in µmol m^{-2} s^{-1}, or the lighting intensity in the PAR waveband in W m^{-2}. The light sum expressed in short wave solar radiation (280-2,800 nm) is usually converted into PAR radiation using a conversion factor of 0.45. For example, a light sum of 200 Wh m^{-2} d^{-1} inside a greenhouse can be converted into 0.45 x 200 = 90 Wh m^{-2} d^{-1} PAR. This, in turn, can be expressed in the units of J cm^{-2} (PAR) since 1 Wh equals 3,600 J. Most scientists agree that the best way to express light is in units of mole of photons m^{-2} per unit of time (seconds or days). However, most growers prefer to use the units of *lux or foot-candles.*

Summation of sunlight and supplemental light
To be able to compare the light sum received from supplemental lighting and from sunlight, sunlight has to be converted into moles of photons. This requires several steps:

- First, global radiation has to be converted into PAR radiation. The global radiation sum is expressed in *joule*, which relates to *watt*. In Table 5.2, Column 2 it is shown that, on average, 45% of sunlight falls in the PAR waveband.
- Second, the light transmissivity of the greenhouse needs to be taken into account. A reasonable number is 60%, in other words, a loss of 40%. However, this percentage may fluctuate considerably depending on season, greenhouse structure, and glazing material.
- Third, the light intensity can be converted into *watts and photons*.

Figure 5.3. ***Kipp-pyranometer (solarimeter).***
This radiometer CM 3 measures global radiation in the waveband between 305 and 2,800 nm at 50% points, or 295-3,200 nm (10% points), or 280-4,500 nm at 1% point. Source: Kipp & Zonen B.V., 2001.

Table 5.3a explained
As an example, the conversion for an average day in April (for Naaldwijk, The Netherlands) is discussed. The average daily global radiation is 1,399 J cm^{-2} (Column 2). Next, J cm^{-2} is converted into mol m^{-2} using a conversion factor of 2.0804/100 (Ting et al., 1987).
In Column 4 of Table 5.3a the transmissivity of the greenhouse structure is taken into account (assumed to

Figure 5.4. ***Light measurements.***

The LI-1800 can be used for various light measurements, including PAR, watt m^{-2}, lux in different wavebands.
The sensor can be mounted on a tripod in order to collect data at sloping sites. Data are stored in a portable data logger.
Source: LI-COR.

Note: The difference between the terms irradiance and fluence rate depends on the geometry of the sensor (Aphalo, 2001). Light flux measured as received on a flat surface and per unit of time is called irradiance. Light flux received on a spherical surface and per unit time is called fluence rate. PPF or PPFD are synonyms for photon irradiance.

Table 5.3a. ***Average daily global radiation in Naaldwijk, 52° N.L., The Netherlands,***
(measured during the period 1961-1980), converted into various radiation units.
Source: Royal Dutch Meteorological Institute (KNMI).

1 **Month**	2 **Outside solar radiation** daily integral *J cm⁻² d⁻¹*	3 **Outside PPF** daily integral *mol m⁻² d⁻¹*	4 **Inside PPF** 60% daily integral *mol m⁻² d⁻¹*	5 **Day-length** *hours*	6 **Outside Intensity** solar radiation *W m⁻²*	7 **Inside Intensity** 60% solar radiation *W m⁻²*	8 **Average Inside Intensity PPF** *µmol m⁻² s⁻¹*	9 **Average Inside Intensity** *lux*	10 **Average Inside Intensity** *ft-c*
January	237	4.9	3.0	8.0	82.1	49.3	103	5,572	518
February	492	10.2	6.1	9.6	142.5	85.5	178	9,667	898
March	851	17.7	10.6	11.5	205.2	123.1	256	13,923	1,294
April	**1,399**	**29.1**	**17.5**	**13.6**	**285.0**	**171.0**	**356**	**19,337**	**1,797**
May	1,787	37.2	22.3	15.4	321.4	192.9	401	21,806	2,026
June	1,963	40.8	24.5	16.5	331.2	198.7	413	22,468	2,088
July	1,845	38.4	23.0	16.0	319.5	191.7	399	21,674	2,014
August	1,561	32.5	19.5	14.4	300.3	180.2	375	20,371	1,893
September	1,062	22.1	13.3	12.4	238.3	143.0	297	16,167	1,502
October	617	12.8	7.7	10.3	165.9	99.5	207	11,252	1,046
November	288	6.0	3.6	8.5	94.3	56.6	118	6,399	595
December	182	3.8	2.3	7.5	67.1	40.3	84	4,554	423

be 60%). The daylength is calculated based on the latitude and the time of the year for the location under consideration (Column 5). Using the daily light sum (Columns 2-4) and the daylength (Column 5), the daily average light intensities (Columns 6-10) were calculated.

For Ithaca, NY, USA the data are in a similar way represented as for Naaldwijk, Table 5.3b. Comparing these two tables, it appears that the differences between the light sums in winter and summer are much higher in Naaldwijk than in Ithaca.

While light sums in June and July are about the same, in December the light sum in Naaldwijk is only the half of Ithaca's. From summer to winter light is decreasing much faster in Naaldwijk than in Ithaca. Nevertheless, for most of the horticultural crops, a severe shortage of light is also apparent in Ithaca from October to February, in Naaldwijk from September to March. At least, in these periods supplemental light is necessary.

An example for the use of supplemental lighting based on the availability of sunlight inside the greenhouse:

Suppose supplemental lighting is provided (HPS, SON-T Plus) at an intensity of 100 µmol $m^{-2}s^{-1}$, as soon as the sunlight intensity inside the greenhouse drops below 100 µmol $m^{-2}s^{-1}$. Based on data presented in Table 5.4a, in April in the Netherlands, the supplemental lighting system could be turned on for 12 hours, in theory. Switching the lighting system on and off is usually done based on measured outdoor light intensities. A set point for supplemental lighting (HPS) in the greenhouse of 100 µmol $m^{-2}s^{-1}$, corresponds with an approximate outdoor solar radiation of 81 W m^{-2}. For crops with higher light requirements, higher light intensities are used ranging between 150 and 250 W m^{-2} of outdoor solar radiation. To prevent lamps from turning on and off regularly during the course of a day (due to a fluctuating sunlight intensity), a range of plus or minus 25 or 50 W m^{-2} around the set point is

Table 5.3b. ***Average daily global radiation in Ithaca, NY, 42°25'N.L., USA,***
(measured during the period 1983-1996), converted into various radiation units.
Source: Cornell University, Ithaca, NY.

1 **Month**	2 **Outside solar radiation** daily integral *J cm⁻² d⁻¹*	3 **Outside PPF** daily integral *mol m⁻² d⁻¹*	4 **Inside PPF** 60% daily integral *mol m⁻² d⁻¹*	5 **Day-length** *hours*	6 **Outside Intensity** solar radiation *W m⁻²*	7 **Inside Intensity** 60% solar radiation *W m⁻²*	8 **Average Inside Intensity PPF** *µmol m⁻² s⁻¹*	9 **Average Inside Intensity** *lux*	10 **Average Inside Intensity** *ft-c*
Jan	461	9.6	5.8	9.2	139.1	83.5	174	9,438	877
Feb	755	15.7	9.4	10.3	203.7	122.2	254	13,821	1,284
Mar	1,149	23.9	14.3	11.7	273.8	164.3	342	18,574	1,726
Apr	1,365	28.4	17.0	13.2	288.0	172.8	360	19,540	1,816
May	1,750	36.4	21.8	14.4	337.0	202.2	421	22,861	2,124
Jun	2,033	42.3	25.4	15.1	374.0	224.4	467	25,372	2,358
Jul	1,966	40.9	24.5	14.8	368.4	221.0	460	24,992	2,322
Aug	1,735	36.1	21.7	13.7	351.0	210.6	438	23,812	2,213
Sep	1,279	26.6	16.0	12.3	289.4	173.7	361	19,635	1,825
Oct	870	18.1	10.9	10.8	223.5	134.1	279	15,165	1,409
Nov	471	9.8	5.9	9.5	137.4	82.4	171	9,318	866
Dec	370	7.7	4.6	8.9	115.6	69.3	144	7,841	729

Table 5.4a. ***Hourly average quantum flux (PPF) inside a greenhouse in μmol m^{-2} s^{-1}, for Vlissingen, 51°27'N.L., The Netherlands.***

The data is based on outside light readings in W m^{-2} (solar radiation), which was converted into indoor data using a 60% light transmissivity and 45% PAR, as well as the conversion of 1 W PAR into 4.6 μmol m^{-2} s^{-1} (for sunlight). This table can be used to determine the number of hours supplemental lighting is needed based on a certain threshold value. For example, the lights could be turned on when the intensity in the greenhouse drops below 100 μmol m^{-2} s^{-1} (solar radiation). By dividing the data by a factor of 1.242, the result shows the solar radiation in W m^{-2}, for example 100 μmol m^{-2} s^{-1} of solar radiation inside the greenhouse corresponds with 81 W m^{-2} outside solar radiation. A table with the original data in W m^{-2} is shown in Appendix 1. These light intensities for Vlissingen, The Netherlands, closely match the values for Naaldwijk, 52°NL, The Netherlands (see Table 5.3).

hour	J	F	M	A	M	J	J	A	S	O	N	D
4-5					27	48	27	4				
5-6				39	117	138	111	58	10			
6-7			31	138	238	256	225	173	83	17		
7-8		24	117	258	369	383	351	303	200	93	17	
8-9	35	103	231	380	493	507	473	427	318	194	76	27
9-10	97	190	320	479	600	611	590	542	417	283	145	83
10-11	152	262	400	551	662	700	676	617	489	338	194	124
11-12	176	301	431	597	683	738	714	652	518	369	207	145
12-13	173	297	425	604	679	738	722	648	510	345	190	142
13-14	134	258	386	551	628	697	691	611	458	279	148	103
14-15	83	190	311	469	542	617	594	524	369	200	86	52
15-16	27	107	217	351	431	497	483	414	256	103	24	7
16-17		27	107	221	301	359	359	276	134	24		
17-18			21	101	169	221	221	145	39			
18-19				14	62	103	93	39				
19-20					7	24	17					

used, for the lamps either to turn on or off, or a time delay is used in the switching system.

In the example of supplemental lighting in April, the light sum provided by the lamps can be calculated as: 100 μmol m^{-2} s^{-1} • 12 hours • 3,600 = 4,320,000 μmol m^{-2} s^{-1} or 4,320,000/10^6 = 4.3 mol m^{-2} d^{-1}. Compared to the natural light sum of 17.4 mol m^{-2} d^{-1} (Table 5.3a), an additional 4.3 mol (or 25%) of light can be provided by the supplemental lighting system.

In Table 5.5, two examples are discussed, showing supplemental lighting (HPS) with an intensity of 100 μmol m^{-2} s^{-1} or 8,500 lux (790 ft-c). In the first example, the lighting set point is set at 150 W m^{-2} (of outdoor solar radiation), in the second at 250 W m^{-2}. Furthermore, the months in which the supplemental lighting system is turned off (May through August) are taken into account. In The Netherlands, the light sum during those months is generally regarded as sufficient. But even during the summer, according to Norwegian researchers, rose production could increase linearly with more light. However, in the summer, the cost of supplemental lighting can be (too) expensive, because the heat generated by the lamps cannot be utilized and has to be removed. In addition, in the summer, prices of greenhouse products are often lower.

The Dutch Research Station PBG recommends, in general, turning the lamps off once an intensity of 150 W m^{-2} of outside solar radiation is reached, or at 100 W m^{-2} for crops with a low light requirement. If during the summer (May through August) no supplemental lighting is used, and the turn-off set point is

Table 5.4b. ***Hourly average quantum flux (PPF) inside a greenhouse in μmol m^{-2} s^{-1}, for Ithaca, NY, 42°25'N.L., USA.***

hour	J	F	M	A	M	J	J	A	S	O	N	D
4-5						2						
5-6				9	47	71	50	14				
6-7			18	89	162	206	171	113	54	13		
7-8	4	32	121	211	315	366	328	264	183	101	31	3
8-9	66	131	253	349	473	523	503	429	328	220	112	55
9-10	165	244	382	469	602	670	659	571	478	334	192	133
10-11	249	343	502	574	691	771	763	683	574	417	246	199
11-12	297	402	570	640	708	822	817	758	613	459	269	242
12-13	307	414	583	630	707	820	817	774	611	445	278	238
13-14	267	379	543	593	665	780	774	725	555	406	240	202
14-15	206	305	453	505	578	687	693	609	450	308	171	143
15-16	119	207	330	377	462	545	560	483	339	183	86	68
16-17	31	96	190	240	320	400	402	323	203	70	15	7
17-18		11	59	117	181	239	245	164	66	4		
18-19			1	19	60	101	98	42	2			
19-20					1	10	8					

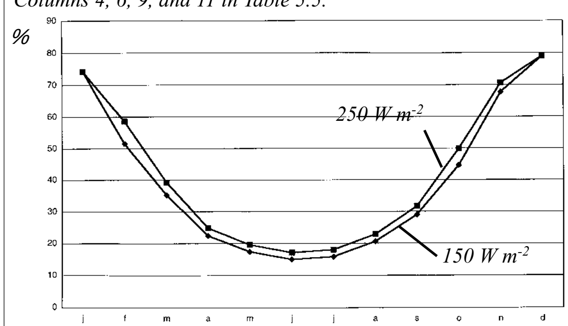
Table 5.5. ***Supplemental lighting compared to natural light inside the greenhouse in Naaldwijk, 52°N.L..***
Supplemental lighting is provided with 400 W-SON-T Plus lamps (HPS) and a light intensity of 100 µmol m^{-2} s^{-1} or 8,500 lux (20 W m^{-2} PAR) for up to 24 hours per day. The lamps are turned on when the light intensity inside the greenhouse drops below 186 µmol m^{-2} s^{-1} (corresponding with 150 W m^{-2} outside solar radiation), Columns 2-6, or below 311 µmol m^{-2} s^{-1} (corresponding with 250 W m^{-2} outside solar radiation), Columns 7-11.
From the data in Table 5.4 it can be calculated for how many hours per day supplemental lighting can be applied, Columns 2 and 7. During the summer, supplemental lighting can be applied as well. Columns 3 and 8 show the number of hours of supplemental lighting per month (Column 2 multiplied by the number of days per month). The daily light sum from supplemental lighting as shown in Columns 4 and 9 are calculated with: number of hours • 3,600 • 100)/10^{6}. Columns 5 and 10 are calculated using the data in Table 5.4. In Columns 6 and 11, the total light sums (from supplemental lighting and sunlight) are shown. From this data, the percentage of supplemental lighting from the total light sum can be calculated (Figure 5.5). In addition, the average annual number of lighting hours has been calculated, and the case in which supplemental lighting is not used from May through August is included. The light intensity and light sum of the solar radiation can fluctuate significantly from year to year as a result of darker or sunnier periods. Fluctuation of plus or minus 50% is not uncommon.

1	2 a	2 b	3 a	3 b	4	5	6	7 a	7 b	8 a	8 b	9	10	11
	Number of hours < 186 *µmol m^{-2} s^{-1}*		**Number of hours lighting/** *month*		**Light sum of lighting per day** *mol m^{-2}d^{-1}*	**Nat.light greenhouse per day** *mol m^{-2} d^{-1}*	**Total light sum greenhouse** *mol m^{-2} d^{-1}*	**Number of hours < 311** *µmol m^{-2} s^{-1}*		**Number of hours lighting/** *month*		**Light sum of lighting per day** *mol m^{-2} d^{-1}*	**Nat.light greenhouse per day** *mol m^{-2} d^{-1}*	**Total light sum greenhouse** *mol m^{-2} d^{-1}*
Jan	24		744		8.6	3.0	11.6	24		744		8.6	3.0	11.6
Feb	18		504		6.5	6.1	12.6	24		672		8.6	6.1	14.7
Mrt	16		496		5.8	10.6	16.4	19		589		6.8	10.6	17.4
Apr	14		420		5.0	17.4	22.4	16		480		5.8	17.4	23.2
May	-	13	-	403	4.7	22.2	26.9	-	15	-	465	5.4	22.2	27.6
Juni	-	12	-	360	4.3	24.4	28.7	-	14	-	420	5.0	24.4	29.4
July	-	12	-	372	4.3	22.9	27.2	-	14	-	434	5.0	22.9	27.9
Aug	-	14	-	434	5.0	19.4	24.4	-	16	-	496	5.8	19.4	25.2
Sep	15		450		5.4	13.2	18.6	17		510		6.1	13.2	19.3
Oct	17		527		6.1	7.6	13.7	21		651		7.6	7.6	15.2
Nov	21		630		7.6	3.6	11.2	24		720		8.6	3.6	12.2
Dec	24		744		8.6	2.3	10.9	24		744		8.6	2.3	10.9

Total hours of lighting, exclusive May to August, with limit on 150 W m^{-2} global radiation outside:	4,515	per year, Column 3a
Total hours of lighting, exclusive May to August, with limit on 250 W m^{-2} global radiation outside:	5,110	per year, Column 8a
Total hours of lighting, during the whole year, with limit on 150 W m^{-2} global radiation outside:	6,084	per year, Columns 3a+b
Total hours of lighting, during the whole year, with limit on 250 W m^{-2} global radiation outside:	6,925	per year, Columns 8a+b
Maximum number of hours per year when lighting for 24 hours (365 x 24 hours):	8,760	per year

set at 186 µmol m^{-2}s^{-1} (inside PAR radiation, which corresponds with 150 W m^{-2}outside solar radiation), then the annual total light sum is 13% lower than when the turn-off set point is set at 311 µmol m^{-2}s^{-1} (which corresponds with 250 W m^{-2} outside solar radiation). If supplemental lighting is also used during the summer months, the annual total light sum increases by 35%. The question is whether the additional yields compensate for the additional expenses. In Figure 5.5, the percentage of supplemental lighting is compared to the total light sum. This percentage fluctuates from 79% in December to 15% in the summer for the examples presented. Note that the duration of supplemental lighting, light intensity, and light sum should be adjusted for each specific crop and cultivar, as well as the timing to turn the lamps on and off.

Figure 5.5. ***The percentage of supplemental lighting as part of the total light sum inside the greenhouse.***
The upper line represents the percentage when the supplemental lighting is turned on at a light intensity below 250 W m^{-2} (outside solar radiation), the lower line when the lamps are turned on below 150 W m^{-2} (outside solar radiation). The data for these curves are shown in Columns 4, 6, 9, and 11 in Table 5.5.



Benefits of supplemental lighting during the darker periods of the year:

1. Quality improvement

More vigorous root systems, larger and firmer leaves, longer and heavier stems, more and bigger flowers with a better color, shorter bedding plants, improved branching. Bud abortion is less likely in lilies, alstroemeria, and chrysanthemum. As a result, the competitive position on the world market can improve.

2. Increase in yield (in weight and quantity)

Higher production levels can be maintained: production starts sooner or continues longer. Increased opportunities for year-round production, resulting in more even distribution of labor requirements. One of the causes of so-called blind shoots in roses is a light-energy shortage, which can be compensated for by using supplemental lighting.

3. Increased resistance against fungi

Fewer problems with Pythium, Rhizoctonia, Botrytis, rust, fungi, mildew, etc..

4. Reduction of the production time

Higher growth rates can result in significant reduction of the production time (several weeks).

Considerable time savings can be realized during flower initiation: flower formation takes a lot of light energy. In chrysanthemum, the response time is considerably reduced.

5. Improvement of post-harvest shelf life

Cuttings are less sensitive to damage and can be transported more easily.

The vase life of cut flowers usually improves.

Pot plants can be transported with fewer losses and survive longer under living room conditions. Reduced incidence of bud abortion and cyathia drop (poinsettia).

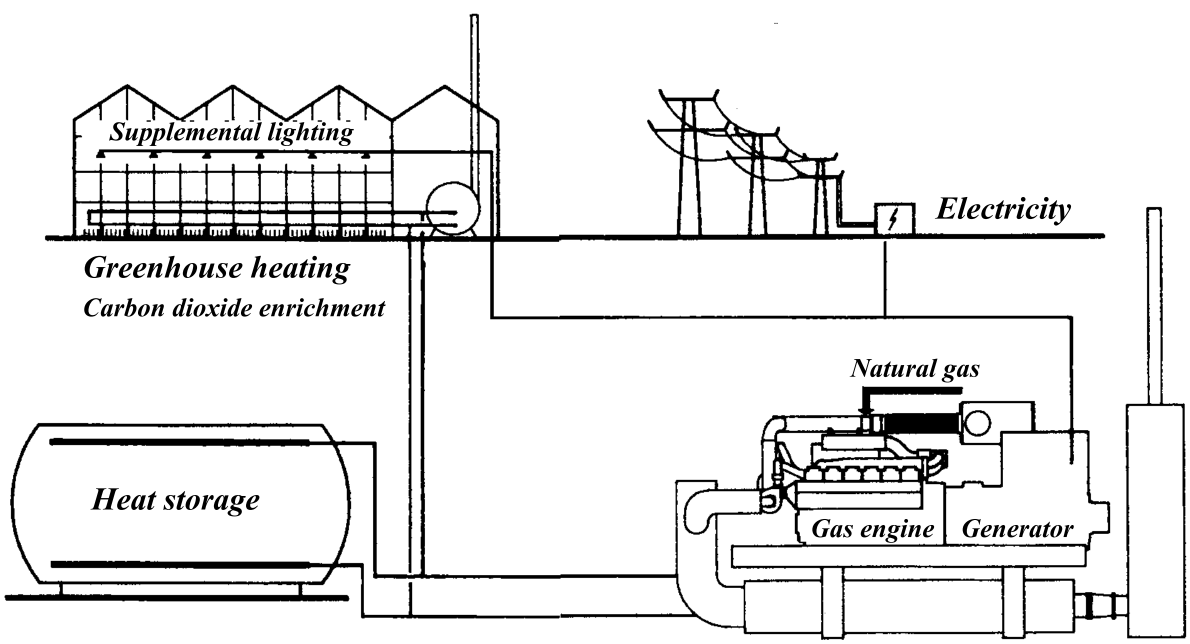
6 Growing Aspects

6.1 Lighting capacity and duration

Introduction

For greenhouse operations, the use of supplemental lighting is a complex issue. The expected increase in production and/or improved quality during the darker winter months should warrant the (high) investment and operating costs. The beneficial effects of supplemental lighting have been discussed earlier. Supply and demand on the (world) market determines the financial returns. For example, Dutch roses grown during the winter without supplemental lighting can no longer compete with roses grown in Africa. However, a winter without crop production is no longer acceptable, both from a business management, labor, or economic point of view. Year-round production requires careful design of nursery and production schedules. Certain crops are grown year-round, *e.g.* cut flowers and pot plants, others are propagated only during certain months of the year. Based on the amount of sunlight, type of greenhouse and light requirements for a given crop, a particular type

Figure 6.1. ***Supplemental lighting and physical lay-out****.*
Prior to the installation of supplemental lighting, the entire production process must be investigated. This may lead to a review of the growing plan, size of the greenhouse operation, labor, energy and carbon dioxide supply. In some cases, such a review indicates the feasibility of a co-gen installation with heat buffer.



of supplemental lighting system can be selected. In order to make certain systems profitable, a cogeneration (electricity and heat) installation and a heat buffer might be necessary (Figure 6.1). Such a system will have a specific effect on the heating method and the greenhouse climate control. The efficiency of a supplemental lighting system increases when the greenhouse air is enriched with carbon dioxide. If enrichment is done using the heating system (using the carbon dioxide present in the exhaust gases), heat is released in the process. Heat is also generated during the generation of electricity with a co-gen installation and during supplemental lighting due to the inefficiency of the bulbs to generate light. The utilization of this excess heat reduces the overall cost of supplemental lighting. For locations at a latitude above 45º N.L., an supplemental lighting installation using 800 SON-T lamps (400 w each) per hectare (2.5 acres) does not lead to considerable excess heat generation for most crops. The heat produced by a co-gen installation can be used efficiently as well. If electricity is obtained from the public grid, the number of lamps installed may increase to as many as 2,000 per hectare (1 lamp for each 5 m^2, or 1 lamp for each 54 ft^2). Higher lamp densities are possible when the heat can be used for alternative uses. This ensures that the heat and carbon dioxide do not have to be vented to the outside. In conclusion, lighting should be considered in relation with many other production aspects. Calculations for pot plants and cut flowers have been made by PBG (Experimental Station) and DLV (Extension Service), ETKO, Van Rijssel, Zwarts (advisors), etc. For supplemental lighting systems, not only the fixture and lamp type are important, but also the required installed capacity per square meter and the lighting strategy. Using careful light measurements, the agreed upon light intensity as discussed with the installer should be checked carefully, because during installing many mistakes can be made (Van Rijssel, 1998/99). The method and height of mounting and are very important. Uniform light distribution is very important for uniform crop production (Lakwijk, 1997; Van Rijssel, 1999). Increasing the efficiency of lighting installations to obtain more light from the amount of energy supplied is becoming a common practice (Vegter, 1999). The light sum, lighting period, and light intensity are all related to the crop light requirements, and each lighting system should be able to provide the proper conditions for the particular crop. Seedlings and cuttings have small leaf areas and are grown at high plant densities. Long light periods with a high intensity are usually profitable under those conditions. The light sum also has an important influence on cutting production. Plant propagation in southern countries with higher light intensities is often more cost-effective than investing in supplemental lighting. In The Netherlands, rooting of chrysanthemum cuttings has almost disappeared. In summary, the use of supplemental lighting strongly depends on the cost of electricity, the type of crop, the heat and light requirements, the cultivar, the crop development stage, and the amount of available sun and supplemental light.

Converting instantaneous light levels and light sums

*For **high-pressure sodium** (SON-T Plus 400 W) light:*

$$1\ \mu mol\ m^{-2}s^{-1} = 85\ lux = 0.2\ Wm^{-2}\ PAR = 7.9\ ft\text{-}c \qquad (1)$$

For the conversion of lux to footcandle: 1 ft-c = 10.76 lux
For lux and ft-c as basis, the conversions are:
1,000 lux = 11.8 $\mu mol\ m^{-2}\ s^{-1}$ = 2.4 $W\ m^{-2}$ PAR = 92.9 ft-c
1,000 ft-c = 126.6 $\mu mol\ m^{-2}\ s^{-1}$ = 25.3 $W\ m^{-2}$ PAR = 10.76 klux

Measurements by the Research Station for Floriculture and Glasshouse Vegetables in Aalsmeer, show variations from 11.9 to 13.4 $\mu mol\ m^{-2}\ s^{-1}$ per 1 klux.
The number of $\mu mol\ m^{-2}\ s^{-1}$ per klux increases as the lamps get older and the lamp voltage is increased.

*For **daylight**, the following conversion can be used:*

$$1\ \mu mol\ m^{-2}s^{-1} = 56\ lux = 0.217\ Wm^{-2}\ PAR = 5.2\ ft\text{-}c \qquad (2)$$

For lux and ft-c as basis, the conversions are:
1,000 lux = 17.9 $\mu mol\ m^{-2}\ s^{-1}$ = 3.9 $W\ m^{-2}$ PAR = 92.9 ft-c
1,000 ft-c = 192.3 $\mu mol\ m^{-2}\ s^{-1}$ = 41.8 $W\ m^{-2}$ PAR = 10.76 klux
The type of weather plays an important part in this conversion, see Table 5.2

Light sum using HPS

$$1\ MJ\ m^{-2}\ PAR = 5\ mol\ m^{-2} = 118\ klxh = 10{,}970\ ft\text{-}ch \qquad (3)$$

***Daylight sum** (45% PAR of total radiation)*

$$1\ MJ\ m^{-2}\ PAR = 4.6\ mol\ m^{-2} = 71.9\ klxh = 6{,}640\ ft\text{-}ch \qquad (4)$$

Light requirements for crops

Based on his observations, Professor R. Moe from Norway classified crops according to their light requirement. His classification is based on the required light sum. The class of plants with a low light requirement comprises of shade plants such as: African violet, Lorraine-begonia, and some foliage plants. Most flowering pot plants have an average light requirement, such as: kalanchoe, poinsettia, pot chrysanthemum and Elatior-begonia. Rose, tomato and cucumber belong to the group with a very high light requirement. Table 6.1 provides data including the necessary light intensities and light sums for optimal

Table 6.1. ***Greenhouse crop classification according to light requirements, including supplemental lighting, necessary for optimal growth.***
In Naaldwijk, the Netherlands, the average of the light intensity in December is 2.3 $mol\ m^{-2}\ d^{-1}$ (Table 5.3). SON-T Plus lamps were used for supplemental lighting.
Classification by Professor R. Moe, 1999.

Light requirement crop	Total required light sum	Supplemental light sum in December in Naaldwijk	Supplemental lighting during 20 hours
(**n**=natural)	$mol\ m^{-2}\ d^{-1}$	$mol\ m^{-2}$	$\mu mol\ m^{-2}\ s^{-1}$
(**s**=supplemental)	**n + s**	**s**	**s**
Low	5 - 10	2.7 - 7.7	37 - 107
Medium	10 - 20	7.7 - 17.7	107 - 246
High	20 - 30	17.7 - 27.7	246 - 385
Very high	> 30	>27.7	>385

growth and development. This data forms the basis for supplemental lighting strategies. During the darkest month of the year, the lamps are used to obtain the desired light sum. Furthermore, a certain degree of excess capacity is needed for periods with fewer than normal sun hours. For example, in December the average light sum in The Netherlands is 2.3 mol m^{-2} d^{-1} (Table 5.3), but it can also be less than half this average. The required light sum is calculated based on the maximum daylength and lighting period of 20 hours (Table 6.1). Therefore, a greenhouse crop with an average light requirement needs (for optimal growth and using high-pressure sodium lamps): 106-244 μmol m^{-2} s^{-1} during 20 h (= 7.6 to 17.6 mol m^{-2} d^{-1}). Under Dutch conditions, supplemental lighting should be provided from August through April. By designing the light intensity of the supplemental lighting system based on the light requirements in December, there is an underutilized capacity during other months of the year. Due to the high investments for supplemental lighting systems, growers usually settle for a sub-optimal compromise. The desired target value should be determined based on quality (thickness of the stems, number, color, and size of the flowers), dry and fresh mass, cultivation period, branching, leaf quality, desired size of the plant (need for space and pot size), etc..

In contrast to the **optimum** values determined by Professor Moe, the LVG Research Station in Hannover-Ahlem has listed values for minimum acceptable growth and development of plants. In order to avoid a long growing period and poor winter quality, a minimum light sum should be provided (Table 6.2). These values are (very) low in comparison with the optimal values.

For the successful use of supplemental lighting systems, growers will have to make a choice between the above extremes. When we discuss the lighting recommendations for individual crops (Section 6.2), these issues will be reviewed again. They will then be compared with current lighting strategies at commercial greenhouse operations. First, however, some more lighting aspects are discussed in detail.

Table 6.2. ***Greenhouse crop classification according to light requirements, including supplemental lighting, necessary during the winter for acceptable levels of plant growth*** *(Hendriks et al., LVG, Hannover-Ahlem, 1993). In Naaldwijk, 52°NL, The Netherlands, the average light sum in December is 2.3 mol m^{-2} d^{-1} (inside the greenhouse). Lighting with SON-T Plus.*

Light requirement crop	Total required light sum PAR *Wh m^{-2} d^{-1}* mainly hps	Total required light sum PAR *mol m^{-2} d^{-1}* mainly hps	Supplemental light sum in December in Naaldwijk *mol m^{-2} d^{-1}* hps
Low	46 - 92	0.8 - 1.6	0.0
Medium	92 - 138	1.6 - 2.5	0.0 - 0.2
High	138 - 184	2.5 - 3.3	0.2 - 1.0
Very high	184 - 230	3.3 - 4.1	1.0 - 1.8

Light intensity

African violets have a low light requirement that can be supplemented using a low intensity. The optimum light intensity is crop specific. An intensity of more than 60 μmol m^{-2} s^{-1} can result in crop damage, growth disorders, or excessive outgrowth of lateral shoots in African violets (Hendriks, 1993), while for roses growth of axillary shoots is only beneficial. The optimum light intensity is much higher for many rose cultivars. For both crops, the goal is to create optimum conditions for photosynthesis.

Light saturation

The leaf photosynthesis of roses is saturated between 800 and 1,000 μmol m^{-2} s^{-1}. For crop photosynthesis, the values for many rose cultivars are higher. Since the other growth factors such as temperature and carbon dioxide tend to fluctuate during many experiments, the data on the maximum rate of photosynthesis tend to differ somewhat.

Professor Moe measured a light saturation for crop photosynthesis for cut roses at 1,000 μmol m^{-2} s^{-1}, and for pot roses at 500 μmol m^{-2} s^{-1}. Therefore, for cut roses, supplemental lighting with an intensity of 100 μmol m^{-2} s^{-1} could be beneficial to photosynthesis and consequently to growth even during the summer.

Switching lamps on and off

In many greenhouse operations, the lamps are switched off when certain light intensity is reached. For roses, this usually occurs at a global radiation (outside the greenhouse) of 200-250 W m^{-2}, or 250-310 μmol m^{-2} s^{-1} (inside) and for low light requiring crops at 10-100 W m^{-2}. For rose production, these light intensities seem rather low, and these values appear not to be based on particular aspects of plant physiology.

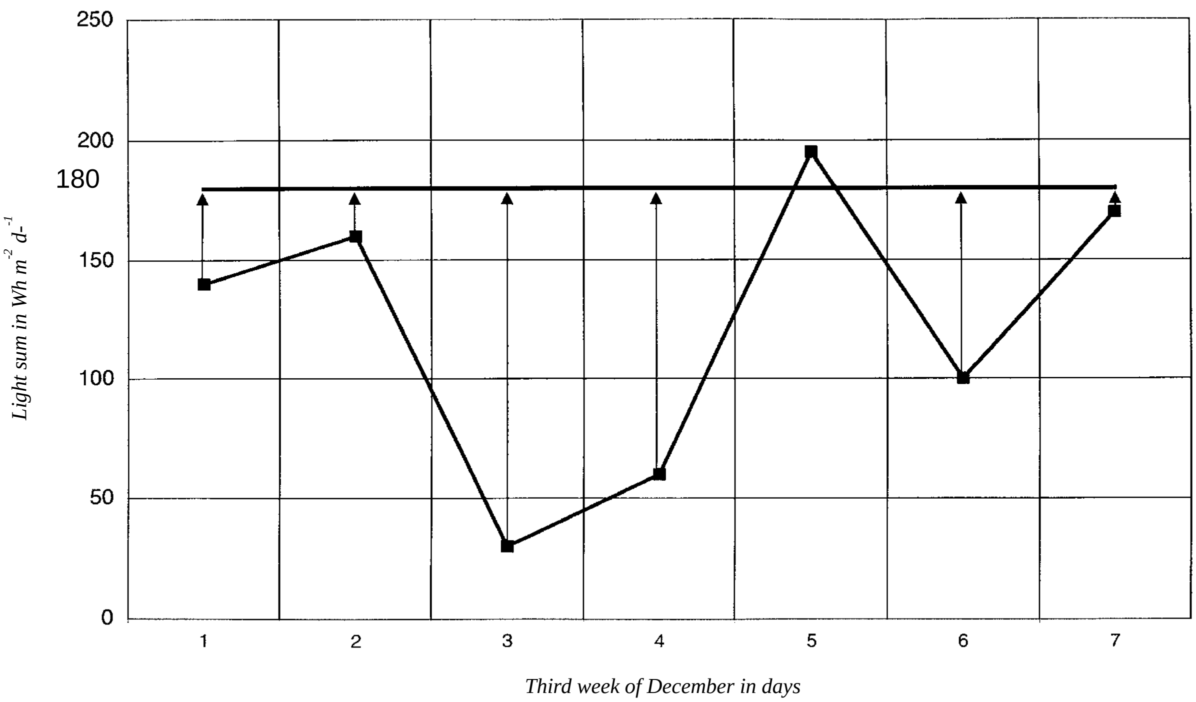
Supplemental lighting as a portion of total radiation during the winter

In December, the light intensity in the greenhouse usually does not exceed 185 μmol m^{-2} s^{-1} or 150 W m^{-2} outside global radiation. If at this intensity the lamps are switched on, as recommended by the research station in Aalsmeer, The Netherlands, and the supplemental light intensity is 33 μmol m^{-2} s^{-1}, the light intensity during day time in the greenhouse is increased with at least 18%. For roses with 100 μmol m^{-2} s^{-1} of supplemental lighting, this is 54%. During the winter period, the natural light intensity increases slowly during the morning. In the summertime, this happens much more quickly. Therefore, during the winter, the lamps are switched off several hours later than during the summer.

Supplemental lighting as a portion of total radiation during the summer

In The Netherlands, from May to July, the average light intensity during the day in the greenhouse is about 400 μmol m^{-2} s^{-1}, with around noon a maximum of 740 μmol m^{-2} s^{-1} (Table 5.4). Under these conditions,

Figure 6.2. ***Supplemental lighting strategy based on a fixed light sum.***
Assume that the target light sum of a crop is 180 Wh m^{-2} d^{-1} of PAR. The daily average light sum during December (in The Netherlands) in a greenhouse with 60% light transmission is about 137 Wh m^{-2} d^{-1} of PAR.
The graph below presents the third week of December with a daily average of 122 Wh m^{-2} d^{-1} of PAR. Varying degrees of deviations may occur on a daily basis. As a result, varying numbers of hours of supplemental lighting need to be provided. Suppose the lighting system has a light intensity of 10 Wh m^{-2} d^{-1} of PAR or 4,250 lux or 50 µmol m^{-2} s^{-1}. In the example given below, on day 5 there was a sufficient (small excess) amount of light in the greenhouse, so that supplemental lighting was not necessary. On day 3, however, there was shortage of 180 - 30 = 150 Wh m^{-2} d^{-1} PAR, so that 15 hours of supplemental lighting with an intensity of 10 Wh m^{-2} h^{-1} of PAR was required.



the potential contribution of supplemental lighting declines significantly. As a result, the lamps remain off during the day. At night, at most 8-10 hours of supplemental lighting can be provided while using a dark period of 4 hours (Tables 5.4 and 5.5). Greenhouse operations using cheaper electricity from a co-gen installation, may consider providing lighting also during the summer at night, particularly for roses with their high light requirements, provided that the generated heat is utilized efficiently. The average supplemental light intensity for rose production has increased in recent years from 50 to 100 µmol m^{-2} s^{-1}, a trend that is also noticeable in other crops with high light requirements.

Controlling by light sum
The contribution of supplemental lighting to the total light sum decreases as the ambient light sum increases (Figure 5.5). For African violets, with a low light requirement, lighting can be stopped earlier in the season than for rose production. For most crops, the production of extra dry matter shows a linear relationship with the light sum. In all cases, a grower must compromise between increased crop production and increased costs to operate the supplemental lighting system. In The Netherlands, supplemental lighting is controlled based on the outdoor light intensity, which results in light sums that may fluctuate considerably from day to day and from season to season. An alternative approach is to provide the plants with a fixed light sum.

Supplemental lighting strategy based on fixed light sums
Using the supplemental lighting system to provide plants with a fixed light sum is presented in Figure 6.2 (using data from Tables 6.1 and 6.2). The research station in Aalsmeer, The Netherlands, does not recommend this method (Verberkt, 1995, Report 14). During spring this leads to fewer hours of supplemental lighting (-15%) and reduced growth in some crops.
This reduction was observed for pot plants where plant mass responded directly to the light sum received. Suppose for example (Figure 6.2), the target light value is 180 Wh m^{-2} d^{-1} of PAR. Based on the light sum obtained from sunlight, a certain number of hours of supplemental lighting is required. Suppose sunlight provided 30 Wh m^{-2} d^{-1} of PAR, then an additional 150 Wh m^{-2} d^{-1} of PAR is needed. If the installation has a capacity of 10 Wh m^{-2} d^{-1} of PAR then supplemental lighting system needs to operate for 150/10 = 15 hours. Using such target light values prevents that an “excess” of light is applied. However, from a physiological point of view, for many plants (with the ex-

ception of shade plants) there is no such thing as an "excess" of light. Computer programs are being developed to obtain the highest possible economic profit from lighting in pot and cut roses (Jagers op Akkerhuis, 1997). For the lighting strategy of pot roses, the light sums provided by natural light over several days are taken into account. Implementing such a strategy could lead to a reduction of the number of operating hours.

Photoperiod

Plants use light as source of energy and information (Section 3.3). Both effects should be taken into account when supplemental lighting is applied. Prolonging the light period with a higher light intensity increases photosynthesis and, consequently, plant growth. However, side effects may develop with respect to development *(photomorphogenesis)*. A well-known example is the daylength effects on flower initiation in short-day and long-day plants, for which in principle a low intensity suffices. Extension of daylength causes delay of flower initiation in chrysanthemum, provided the daylength is longer than the critical daylength. Through supplemental lighting with high-pressure sodium lamps (HPS), both the photosynthesis and the photoperiodicity (daylength sensitivity) of chrysanthemum can be influenced. As a result, the duration of supplemental lighting during the short-day period when bud initiation and flowering take place, is limited.

Daylength may also affect the elongation rate of plants, for example of cucumber and Easter lilies. In some plant species flower buds are formed both under short-day and under long-day regime (day-neutral plants). However, the rate at which this happens is influenced by the daylength. The flower initiation rates of gerbera, begonia, and freesia increase with reducing daylength. This is considered a quantitative effect of the daylength. The same is true for a short-day plant like year-round chrysanthemum. The number of flowers that will ultimately grow out in these crops will be mainly determined by the light sum, or in other words by the quantity of photosynthates.

Color spectrum

The color spectrum of the lamps greatly affects the photoperiodic effect. Therefore, HPS lamps are effective in keeping chrysanthemums vegetative but not for inducing flowering in long-day plants such as carnation. However, it appears that chrysanthemums grown under supplemental and photoperiodic lighting seem to develop problems when an excessive amount of red light is applied during the day. The carbon dioxide concentration in the greenhouse appears to increase strongly as soon as the lamps are switched on. Apparently, the uptake of carbon dioxide stagnates at this point. This only happens in November when lighting is applied at 50 $\mu mol\ m^{-2}\ s^{-1}$ or more. Later, this phenomenon disappears. Possible reasons are now being investigated.

Dry matter partitioning

Extending the daylength by using supplemental lighting may influence the partitioning of sugars, for example in the tuberous crops such as ranunculus and freesia. Due to the daylength effect, more sugars are transported to the tuber, which may be at the expense of the inflorescence. In freesia, this phenomenon is observed under a daylength ranging between 16 and 20 hours (Berghoef, 1991).

Dark period

The requirement of a dark period (*e.g.* 4 – 6 hours), can be a limiting factor for the duration of supplemental lighting. This phenomenon is observed in certain rose cultivars, tomato and various pot plants. For African violet, an 8-hour dark period is recommended. In the next section, plant disorders are discussed that are related to photoperiod and dark period. Occasionally, plant growth increase appears to slow down or stop altogether under an increasing light period. Using the same light sum, the growth of begonia Elatior, chrysanthemum, hedera, kalanchoe and geranium usually improves more when the light period increases from 12 to 18 hours, or from 16 to 20 hours, than when the light period increased from 18 to 24 hours or from 20 to 24 hours (Gislerød, 1989). For chrysanthemum, geranium and begonia, the economic optimum for the photoperiod is probably between 18 and 20 hours. The keeping quality (vase life) of Begonia Elatior 'Rosanna' and 'Renaissance' declines when the photoperiod exceeds 20 hours (De Beer, 1992), and leaf yellowing may develop as well.

Sometimes a long photoperiod with a low light intensity improves growth more than a short period with a high intensity. A classical example is the rose. Research at AB-DLO with 'Mercedes' rose plants, with only one or two shoots, indicated that at a light sum of 8.4 $mol\ m^{-2}\ d^{-1}$ the extension of the photoperiod from 12 to 18 hours increased the plant weight with 10% and the number of flowering shoots from 6% to almost 30%. Prolonging the photoperiod from 13 to 20 hours, on the other hand, had an adverse effect on plant mass and the number of flowering shoots (Bakker, 1997). Other rose experiments showed comparable results.

A light intensity of 204 $\mu mol\ m^{-2}\ s^{-1}$ for 24 hours resulted in an increase in dry matter production in roses of 80% compared to 410 $\mu mol\ m^{-2}\ s^{-1}$ for 12 hours (Jiao, 1991). Apparently, the plant uses a lower light intensity more efficiently. The challenge is that the optimum photoperiod within a given crop differs with each cultivar, as is the case with dieffenbachia. Research with cultivar 'Camilla' showed that a light period of more than 15 hours is detrimental (discoloration of white parts to green), while for cultivar 'Compacta' a light period of 18 hours is optimal. Chapter 4 covers the background of the photoperiod in great detail.

Disorders

Excessive light sums and/or intensities may lead to cup-shaped leaves with hardened brittle leaf stalks (petioles) in Sinningia and African violets. As a result, leaves easily break during packing and shipping. In addition, African violets tend to make multiple hearts due to branching (Hendriks, 1993).

High intensities and/or long photoperiods may result in chlorosis (yellowing) of the leaves in green plants, for example radermachera, ficus and dieffenbachia. Variegation in dieffenbachia may be reduced as white parts of the leaves become green (Hendriks, 1993).

Roses, which are lit too long, may produce large leaves, so that the leaf/flower ratio is unfavorably affected.

Dieback of leaf margins or tips (necrosis) after application of pesticides is sometimes believed to be caused by higher leaf temperatures as a result of supplemental lighting. It is therefore recommended to turn the lamps off at least two hours before application.

Growing roses under a photoperiod longer than 18 hours (especially during extended periods) may lead to disruptions with opening and closing of the stomates (Slootweg, 1991; Mortensen, 1999). During vase life, this leads to quality problems such as increased transpiration, desiccation, and leaf drop. The desiccation should be regarded as tissue damage due to the increased uptake of preservatives (including sugars, bactericides, wetting agents, etc.).

Finally, the pot plant schefflera may suffer leaf drop in addition to increased elongation of the internodes as a consequence of excessive lighting (Hendriks, 1993).

6.2 Lighting Recommendations for Various Crops

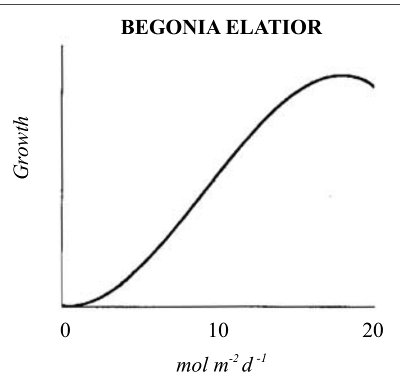
6.2.1 Stock Plants

Introduction

Stock plants (mother plants) grown for the production of cuttings are lit during the winter months to achieve sufficient productivity. In addition, a number of qualitative aspects of the cuttings are improved by lighting, such as weight, number of flowers, firmness, vigor, resistance against fungal diseases, as well as the degree and rate of rooting. The desired intensity and duration depend on the specific crop and cultivar. Due to the higher leaf area index (LAI) of the stock plants, the lighting requirement is often higher than for the production of pot plants.

Argyranthemum frutescens

This is a quantitative LD plant, indigenous to the Canary Islands (Horn, 1996). It responds very strongly to light. For cutting production, the minimum target value for supplementary lighting is 70 $\mu mol\ m^{-2}\ s^{-1}$ (Hendriks, 1993). In order to keep the crop vegetative, temperature and photoperiod are important. For research purposes, a daylength of 8 hours is maintained. Flowering can be promoted for the most important cultivar ‘Silver Leaf’ by applying 4 weeks of low temperatures (12-16ºC) under short-day followed by a long-day regime (Johansson, 1973; Horn, 1996). Plant height is controlled by either red or blue light, similar as with chlormequat or Cycocel (Jatzkowski, 1993). Furthermore, high temperatures delay flower induction.



Begonia Elatior is a quantitative short-day (SD) plant. Flower induction can also take place due to other factors and conditions, such as plant age, temperature and light quantity. Frequently, two or more factors are active simultaneously. In addition, there are cultivar differences. ‘Athen’ does not respond to SD, ‘Barkos’, ‘Renaissance’, ‘Pinto’ and ‘Ann’ do. The higher the temperature, the stronger the response to short-day (Verberkt, 1997). Critical daylength is 13 hours, which depends greatly on temperature. Stock plants can be kept vegetatively by a photoperiod of at least 16 hours and a high temperature level of 24°C. The light requirement of the crop is average (Tables 6.1 and 6.2).

6.2.1 STOCK PLANTS
- ***Introduction***
- ***Argyranthemum frutescens***
- ***Begonia Elatior hybrids***
- ***Campanula isophylla***
- ***Chrysanthemum***
- ***Dianthus caryophyllus (standard or spray Carnation)***
- ***Euphorbia pulcherrima (Poinsettia)***
- ***Fuchsia***
- ***Hibiscus rosa-sinensis***
- ***New Guinea Impatiens***
- ***Kalanchoe***
- ***Pelargonium Zonal and Peltatum hybrids (Zonal and Ivy Geraniums)***

Begonia Elatior hybrids

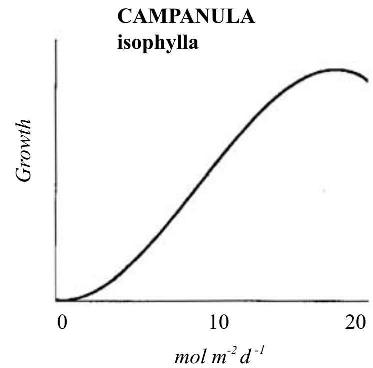
This type of begonia is a quantitative short-day plant that may flower also without short day. Photoperiod and temperature have an important influence on flowering, but also on vegetative growth, root and shoot initiation of cuttings (Bertram, 1989; Custers, 1986/1987; Karlsson, 1992). It is recommended to give stock plants for leaf cutting production a short-day period of 4 weeks, because leaves of generative plants produce more breaks and root better. The necessity of short-day for flowering declines proportionately with the decrease in temperature (from 24 to 12ºC). The critical daylength at 24ºC is 12.5-13 hours. Above 24ºC, the daylength sensitivity becomes qualitative and this response is cultivar dependent.

In order to maintain vegetative growth for shoot cutting production, a combination of long-day (16-20 hours) and a high temperature (24-26ºC) is needed (Anon., 1997; Verberkt, 1997). Daylength extension can be given by way of supplemental and photoperiodic lighting.

Begonia Elatior has an average light requirement of 10-20 $mol\ m^{-2}\ d^{-1}$. For good growth during the winter in The Netherlands, supplemental lighting with an intensity of 40-50 $\mu mol\ m^{-2}\ s^{-1}$ is necessary. In certain cultivars, a high light intensity may lead to shoot cuttings that flower prematurely (Hendriks, 1993). Lighting stock plants to a daylength of 22 hours results in the highest number of shoots for various cultivars. The increase in cutting production was estimated at 30%. In The Netherlands, photoperiodic lighting is necessary from mid-August to the end of March. The daylength can be extended to 16 or 18 hours with a light intensity of 1 $\mu mol\ m^{-2}\ s^{-1}$, using either fluorescent, incandescent, or HPS lamps. The required installed luminaire capacity is 3-5, 15 and 5 $W\ m^{-2}$, respectively, without ballast. When using incandescent lamps, cyclic lighting can be applied (*e.g.* 10 minutes on during each half-hour), at a minimum installed lamp capacity of 15 $W\ m^{-2}$.

Campanula isophylla

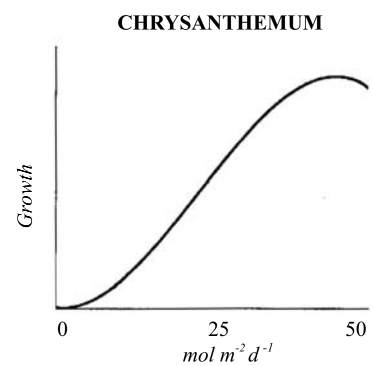
This is a qualitative LD plant with a critical photoperiod of 14-16 hours depending on the temperature. At 12 to 15ºC it is 16 hours, at 18ºC 15 hours, and at 21ºC 14 hours. Stock plants remain vegetative at a photoperiod of 12 hours, with an accompanying temperature of 15-18ºC.
The increase in cutting production through lighting can be spectacular. An increase in light intensity from 28 to 87 $\mu mol\ m^{-2}\ s^{-1}$ with SON-T lamps during 12 hours increased production during a 24-week cutting period with 245%. Carbon dioxide was also supplied at a concentration of 900 ppm. To obtain the same number of cuttings, without carbon dioxide enrichment, required a light intensity of 150 $\mu mol\ m^{-2}\ s^{-1}$. Therefore, the effect of carbon dioxide enrichment is impressive. The minimum required light sum is 3.8 $mol\ m^{-2}\ d^{-1}$. Cuttings of lit plants take root better and develop better than those of unlit plants (Moe, 1976).



Campanula isophylla is a qualitative LD plant. The critical daylength varies between 14 and 16 hours, depending on the temperature. A 12-hours photoperiod is maintained for vegetative growth. The crop has a medium light requirement.

Chrysanthemum

The effect of lighting on chrysanthemum stock plants is illustrated in Table 6.3. Not only the number of cuttings increases but also the rooting and subsequent growth of the cuttings. Chrysanthemums have a very high light requirement. The (relative) growth rate during summer is 3.5 times as high as during winter. According to Cockshull (1972), for optimum growth and flowering, the light level during a large part of the day should be higher than 600 $\mu mol\ m^{-2}\ s^{-1}$. In The Netherlands, this light intensity can often be observed in the greenhouse starting in the second half of April (Table 5.4). The corresponding light sum is then higher than 17 $mol\ m^{-2}\ d^{-1}$. Beyond this light sum, the yield per square meter keeps increasing further. The minimum light sum is between 4.6 and 6.9 $mol\ m^{-2}\ d^{-1}$. If natural light is taken into consideration, a light intensity of at least 60 $\mu mol\ m^{-2}\ s^{-1}$ is necessary for 20 hours, which means an extra light sum of 4.3 $mol\ m^{-2}\ d^{-1}$. Applying this in December in The Netherlands, the total light sum can be increased to approximately 6.6 $mol\ m^{-2}\ d^{-1}$. This is about the same light sum as occurs on average in a greenhouse during the second half of February in The Netherlands.
To prevent total inhibition of flower initiation in stock plants of all cultivars, a daylength of 20 hours is necessary. This can also be accomplished by night interruption with HPS lamps. The minimum light sum that is required needs to be further investigated.
Another approach is to provide photoperiodic lighting using incandescent lamps at an intensity of 2.1 $\mu mol\ m^{-2}\ s^{-1}$. This can be done both cyclically and continuously, as night interruption over a 5-hour period. The cyclic lighting can be provided for 10 minutes during every 30-minute period. Rooting of cuttings is promoted with supplemental lighting for 4 to 5 days with 35 $\mu mol\ m^{-2}\ s^{-1}$, combined with carbon dioxide enrichment. Based on growth chamber experiments, the optimal growth conditions are high temperatures of 23/31ºC (N/D) and a light intensity of 69 $\mu mol\ m^{-2} s^{-1}$ (ETKO, 1997).



Chrysanthemum is a quantitative SD plant. The critical daylength ranges from 10 to 12 hours. For vegetative growth, a photoperiod of 16 hours or more is needed. Safe boundaries for generative and vegetative growth are between 10 and 20 h, depending on the cultivar and the season. The crop has a very high light requirement.

Table 6.3. ***The effects of supplemental lighting on chrysanthemum stock plants.***
Cv 'Horim' during the first 4 weeks after planting.
Source: Borowski, 1981.

Lighting intensity $\mu mol\ m^{-2} s^{-1}$	Number of roots	Plant height cm	Dry mass young plants gram	Increase (rel.) in dry matter %
36	31.1	29.5	2.7	100
73	37.8	32.8	3.3	122
145	36.6	33.3	3.5	129

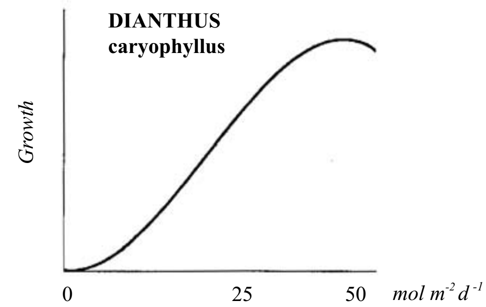
Installed capacity of incandescent lamps (150 W) and light yield. Measurements at 2 m under the lamp*. Source: PBG, 1996.*

light intensity $\mu mol\ m^{-2} s^{-1}$	average intensity $\mu mol\ m^{-2} s^{-1}$	watt per 10 m² floor area	number of lamps per 10 m² installed capacity
1.5-2.0	1.75	15	1

To obtain the same light intensity using the compact fluorescent lamps (PLE - 20 W), 4 times as many lamps are required; while only 3 times as many using fluorescent TL-33 and SOX, both 18 W.

Dianthus caryophyllus
(standard or spray Carnation)

Carnations require high light levels and are a quantitative LD plant. Light saturation is not likely to occur, as is apparent from the uptake of carbon dioxide by leaves of 'Cerise Royalette'. The net photosynthesis continues to increase up to 2,250 µmol m^{-2} s^{-1} (Halevy, 1989). To maintain an adequate growth rate of the crop, supplementary lighting should be applied (in The Netherlands) from September through mid-April with an average target value of 20 mol m^{-2} d^{-1}. This means that the light intensity during a large part of the day exceeds 385 µmol m^{-2} s^{-1}. This is economically far too high for supplemental lighting for cutting production. It is clear, though, that the intensity of 30 µmol m^{-2} s^{-1} (which is a common intensity used in commercial operations) is far too low for rapid growth. This is even more obvious when daylength is taken into consideration, because the lighting period of stock plants is restricted to a maximum photoperiod of 14 hours. Under SD conditions (< 14 hours), the shoots remain vegetative for a longer period while branching is stimulated, which is desired for cutting production. LD inhibits the growth of shoots with fewer than 5 full-grown leaf pairs, as well as the sprouting of lower positioned axillary buds. Short-day results in improved quality of cuttings that root better than cuttings grown under LD (Pokorny, 1960). LD, however, stimulates the rooting process itself, so that supplemental lighting can be applied at that time.

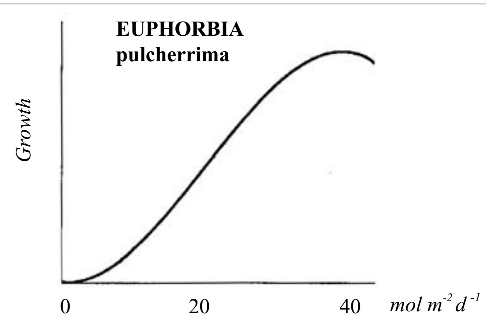


Standard and spray carnations are quantitative LD plants. The critical daylength is 14 hours. SD regime stimulates branching of the stock plants. The crop has a very high light requirement.

Euphorbia pulcherrima (Poinsettia)

A high light sum during cutting production has favorable effects: increase of cutting production, better and uniform sprouting of axillary buds, and therefore a more uniform architecture of the stock plants. It also leads to rapid leaf initiation and development, and thus a reduced period between cuttings. The strength of the attachment of the lateral shoots is improved while the older leaves adjust themselves to higher light intensities. This results in reduced leaf damage and a higher photosynthetic activity under increased irradiation.

The minimum for optimal side shoot formation is 100 klxh d^{-1}(Ludolph, 1994). This corresponds with a light sum of approximately 400 Wh m^{-2} d^{-1} PAR or 6.6 mol m^{-2} d^{-1}. This can be achieved with a light intensity of 184 µmol m^{-2} s^{-1} for 10 h. In Spain and Portugal, the light sum remains above 6.6 mol m^{-2} d^{-1} even during the winter months, and therefore complies with this minimum requirement. Therefore, successful propagation can be realized in these countries without supplemental lighting, but with photoperiodic lighting.



Poinsettias are quantitative SD plants. The critical daylength is 12.5-13 hours. The stock plants are kept vegetative at a daylength of at least 14 hours or with night interruption.
The stock plants have a very high light requirement.

In Oslo, the light sum is less than 6.6 mol m^{-2} d^{-1} from September through March. Therefore, supplemental lighting is provided at an irradiance of 60-70 µmol m^{-2} s^{-1} for 20 hours. In The Netherlands, the same lighting duration at an intensity of 60 µmol m^{-2} s^{-1} is recommended in December to obtain a total light sum of 6.6 mol m^{-2} d^{-1}. Under normal conditions, this sum is not reached in The Netherlands from mid-October through February (Table 5.3). Since the above mentioned light sum is the minimum requirement, supplemental lighting is required for the start of 'Elite' mother plants (*i.e.* during the period from the end of September through February) and also during the start of stock plants from mid-February through mid-April (for Dutch conditions). Light saturation of the leaf photosynthesis in stock plants was observed above 500 µmol m^{-2} s^{-1} (Lange, 1984).

There are differences between cultivars in light sum requirement: Gutbier cultivars, for example, can do without supplemental lighting two weeks sooner than 'Lilo'. To keep the stock plants vegetative, a photoperiod of at least 14 hours is regarded as a safe minimum. Therefore, for the Dutch conditions, the daylength must be prolonged with 2 to 6 hours from mid-September through mid-April. The critical daylength is 12.5 to 13 hours, depending on the cultivar and the temperature. If supplemental lighting is not provided, incandescent lamps are needed with a minimum installed lamp capacity of 10 W m^{-2} of floor area for nightbreak. Under natural conditions during the propagation of young stock plants, a maximum of 540 µmol m^{-2} s^{-1} is allowed until sprouting of the lateral shoots, and subsequently 890 µmol m^{-2} s^{-1} for dark-leaved cultivars, and to up to 1,160 µmol m^{-2} s^{-1} for the light green leaved cultivars. In general, the light levels for stock plants should not exceed 1,200 µmol m^{-2} s^{-1} (Ecke, 1990). This illustrates that these plants can withstand very high light levels. In (sub)tropical countries, poinsettias grow outdoors in the garden and thus the plants are capable of adjusting to various light conditions. In The Netherlands, light levels in the greenhouse rarely exceed 750 µmol m^{-2} s^{-1}. Since high light levels often go together with high greenhouse temperatures, shade curtains are used, mostly from April onwards. In addition to leaf necrosis, high temperatures may also cause excessive elongation of the internodes.

Fuchsia

To avoid premature flowering in these LD plants, a maximum of 11 hours of supplemental lighting at an intensity of 35 µmol m^{-2} s^{-1} is recommended during the daytime in order to maintain a dark period of 13 hours. The light requirement varies greatly among cultivars, so that application of the light sum rule is not possible (Hendriks, 1993).

Hibiscus rosa-sinensis

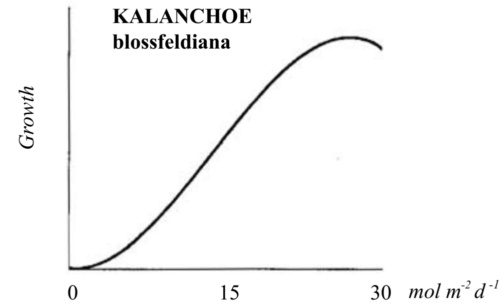
This evergreen shrub is indigenous to tropical Asia. It has a high light requirement and a day neutral response. For optimal growth, the recommended light intensities are between 400 and 1,300 µmol m^{-2} s^{-1} (Dole, 1999). For the production of cuttings, stock plants are lit. Light sums of 5.2 mol m^{-2} d^{-1} or more are needed for optimal branching, with supplemental light intensities of at least 50 µmol m^{-2} s^{-1}.

New Guinea Impatiens

New Guinea impatiens is daylength neutral (Erwin, 1995), and responds very strongly to light. A light intensity of 600 µmol m^{-2} s^{-1} is regarded as a lower limit and 1,000 µmol m^{-2} s^{-1}as the upper limit for optimal growth (Erwin, 1992). Higher light intensities and corresponding higher temperatures can delay growth and reduce the development of leaves and/or flowers. Cutting production, therefore, increases linearly with an increase in light intensity. A minimum intensity of 70 µmol m^{-2} s^{-1} is recommended (Hendriks, 1993).

Kalanchoe

Stock plants need high light levels. The desired light sum is between 20 and 30 mol m^{-2} d^{-1}. At 22ºC a light intensity of 930 µmol m^{-2} s^{-1} in the greenhouse is regarded as optimal. Above this level, which rarely occurs in The Netherlands, shade curtains are used (Pertuit, 1992). This SD plant has a critical daylength of 11-11.5 hours. To keep the plants vegetative, daylength extension is necessary between September 1 and April 1 creating a minimum daylength of 13 hours. For this purpose incandescent lamps can be used with an installed lamp capacity of 5 to 7 W m^{-2} of floor area, while fluorescent lamps may suffice as well. Supplemental lighting has taken the place of photoperiodic lighting for stock plants. Most stock plant producers and cutting propagators use supplemental lighting. The shoot formation increases proportionately with the lighting duration. Therefore, a lighting duration of 16-20 hours is used with an intensity of 40 µmol m^{-2} s^{-1}. Higher light intensities would give little additional effect (Dole, 1999).



Kalanchoe is a SD plant with a critical daylength of 11-11.5 hours. The stock plants are kept vegetative at a daylength of at least 13 hours.
The stock plants have a high light requirement.

Pelargonium Zonal and Peltatum hybrids

(Zonal and Ivy Geraniums)

Pelargonium Zonale (zonal geraniums) and Peltatum (ivy geraniums) are indigenous to South Africa, where high light levels are normal (30° S.L.). At light intensities below 40 µmol m^{-2} s^{-1}, they do not grow; while at levels between 40 and 190 µmol m^{-2} s^{-1}, growth is slow (Fischer, 1994/1995). Geranium cultivars are day neutral. P. Peltatum has a lower maximal light intensity than P. Zonale. In the first group the optimal light level varies from 400 to 600 µmol m^{-2} s^{-1}, depending on the cultivar. For the second group light levels range from 600 to 1,000 µmol m^{-2} s^{-1} (Fonteno, 1992). Saturation of the leaf photosynthesis of P. Zonale is reached between 700-1,100 µmol m^{-2} s^{-1} (Armitage, 1981). Lighting of P. Zonale can be done up to 18 hours/day at 70 µmol m^{-2} s^{-1}. This can increase cutting production with 100%. High light levels may cause premature dieback of the older leaves. Increasing the RH can counteract this. Leaf drop during cutting production can be avoided by lighting during rooting under sufficient mist at 18 to 20ºC.

Tabl 6.4. ***An example of supplemental lighting of greenhouse crops based on light level in the greenhouse (GH) and light requirement of the crop, using a minimum light sum of 10 mol m^{-2} d^{-1}*** *(Table 6.1).*

	Avg. daily light intensity in the GH	Avg. daily light intensity in the GH	Avg. daily light sum in the GH	Add. daily light sum for 10 mol m^{-2} d^{-1}	Required light intensity when using HPS light during 18 hours			24 hours
	W m^{-2} PAR	µmol m^{-2} s^{-1}	mol m^{-2} d^{-1}	mol m^{-2} d^{-1}	W m^{-2} PAR	klx	µmol m^{-2} s^{-1}	µmol m^{-2} s^{-1}
October	44	200	7.6	2.4	7	3.1	37	28
November	25	113	3.6	6.4	20	8.4	99	74
December	18	83	2.3	7.7	24	10.1	119	89
January	22	101	3.0	7.0	22	9.1	108	81
February	37	172	6.1	3.9	12	5.1	60	45

6.2 Lighting Recommendations for Various Crops

6.2.2 Lighting during (seedling) production of greenhouse vegetable crops

Introduction

Tomato, sweet pepper, cucumber and aubergine are crops with a high to very high light requirement. During the winter months in The Netherlands, growth and quality of the flowers decline to such an extent that production is hardly possible. The interest in using supplemental lighting during crop production is growing strongly in The Netherlands. Traditionally, in autumn and spring, production is switched to different crops. During that period, seedlings are grown for the next crop with the help of supplemental lighting, usually in specialized (propagation) greenhouse operations.

Supplemental lighting is provided by these greenhouse operations using light intensities of 25-50 $\mu mol\ m^{-2}\ s^{-1}$. The beneficial effect of lighting is supported by research data. For tomato, cucumber and sweet pepper seedlings, the required time for a doubling of the dry matter content is shortened significantly between mid-November and mid-February (for Dutch conditions). The largest reduction occurs in December: 20% using a light intensity of 50 $\mu mol\ m^{-2}\ s^{-1}$, and 12% at an intensity of 25 $\mu mol\ m^{-2}\ s^{-1}$, using 10 hours of supplemental lighting in the greenhouse (Figure 6.3). These trends are valid for all three crops. As Figure 6.3 shows, a lighting intensity above 50 $\mu mol\ m^{-2}\ s^{-1}$ provides little further increase in growth rate. From April to early September the (relative) growth rate of young plants remains equal. The light sums during that period in the greenhouse are on average higher than 300 $J\ m^{-2}\ d^{-1}$ PAR or 13.8 $mol\ m^{-2}\ d^{-1}$. During December and January and for a light sum of 50 $J\ m^{-2}\ d^{-1}$ PAR or 2.3 $mol\ m^{-2}\ d^{-1}$, each percent increase or decrease

Figure 6.3. ***Time period (days) for doubling the dry mass of tomato seedlings from 220 to 440 mg.***
Plants were raised in a greenhouse with 65% light transmission under a 10-hour lighting period with various lighting intensities.
Source: G.T. Bruggink, 1987.
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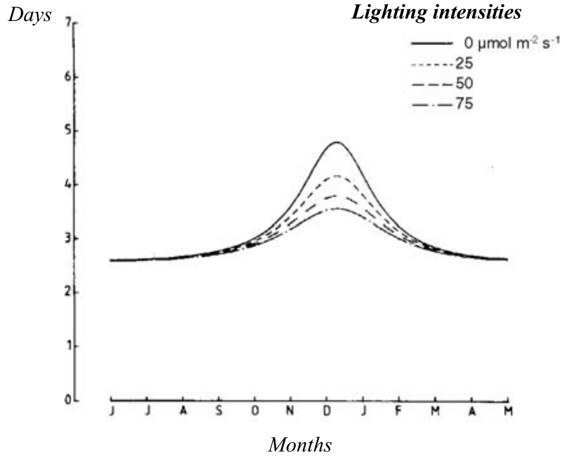


6.2.2	SEEDLING PRODUCTION OF GREENHOUSE VEGETABLES
	- Introduction
	- Seeding
	- Plant raising
	- Eggplant (Aubergine)
	- Cucumber
	- Sweet pepper
	- Tomato

in light results in an increase or decrease of the growth rate of young plants with 0.6%. This is 0.4% at 4.6 $mol\ m^{-2}\ d^{-1}$ from early November to early February. The sensitivity to light, however, also decreases with the increase of plant mass (from 20 to 2,460 mg dry mass). For tomatoes, a daily light sum of 4.6 $mol\ m^{-2}\ d^{-1}$ is regarded as a suitable minimum (Bruggink, 1987). Supplemental lighting can be used to achieve this in order to obtain an adequate growth rate and an undisturbed development of the first flower truss. At an average (natural) light sum in the glasshouse of 2.3 $mol\ m^{-2}\ d^{-1}$ in December, the total light sum can be raised with 16 hours of lighting at 50 $\mu mol\ m^{-2}\ s^{-1}$. In Canada, a level of 100 $\mu mol\ m^{-2}\ s^{-1}$ has given very good results (see Section 6.2.7).

Seeding

Currently, tomato, sweet pepper, and eggplant are mostly sown in plugs, while cucumber is sown first in a germination tray and transplanted later. Precision seeding avoids elongation of the seedlings, which tends to occur with hand sowing. Increased elongation is caused by a high far-red/red light ratio provided to the seedlings. Lighting with red light at the end of the day inhibits elongation. Daylength extension with high-pressure sodium lamps can prevent elongation.

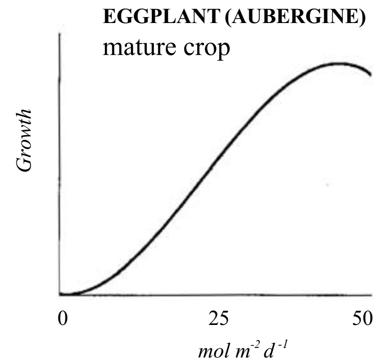
The elongation is influenced by the pigment phytochrome. This pigment also influences the germination of tomato seed. Red light promotes, far-red inhibits the germination. For the germination of cucumbers, a high temperature of 27-30°C is required, while for the other species approximately 25°C is used. To obtain these temperatures, the seeding/plug trays are placed on a concrete floor with (controllable) soil heating. They are covered with plastic to maintain a RH of 100%. The seedlings are subsequently pricked out and potted in transplanting pots.

Seedling growth

During seedling growth, the seedlings are spaced depending on growth period and requests by the buyer. Temperatures are also continuously adjusted during the various growing stages. During seedling production, light intensities of 25–32 μmol m^{-2} s^{-1} are maintained. These levels are not optimal (see Section on tomato). Lighting periods vary with individual crops (see below).

Eggplant

The eggplant originates from (sub)tropical India and China. Traditionally, the crop is grown outdoors in tropical and Mediterranean countries. This implies the crop has very high light and temperature requirements. Immediately after sowing, a 24-hour temperature of 25-26°C is maintained, while during seedling production, a temperature of 22-23°C is maintained. Eggplants require a minimum dark period of 4 hours. When the dark period is shorter, the incidence of chlorosis and growth inhibition increases (Klapwijk, 1986).



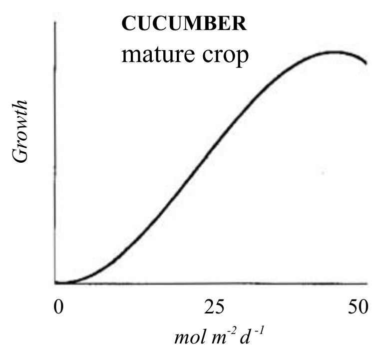
Eggplant belongs to the family of the nightshades or Solanaceae.
The temperature and light requirement are very high. The eggplant needs a daily dark period of at least 4 hours.

Cucumber

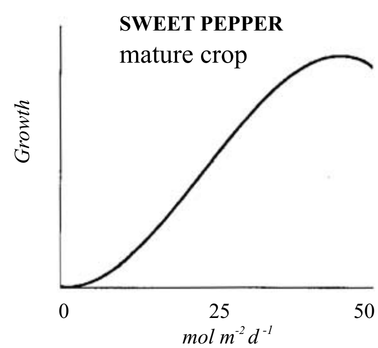
The cucumber originates from (sub) tropical climates, as is apparent from the high germination and growing temperatures. Seed germination takes place in germination chambers at 27-30°C in a very porous substrate such as sawdust or perlite. After several days, the seedlings can be transplanted into the final pot. Direct sowing into the final container is another possibility. Cucumber plants can be lit for 24 hours, which is often done during the period between sowing and transplanting. During seedling production, 24 hours lighting can be applied, but it is sometimes shortened because of the lighting costs per plant. As a result of supplemental lighting, cucumber plants get bigger leaves, grow faster, and have an increased early yield. During production, the plants remain more compact and are therefore easier to handle. Research in Norway showed that when the plants matured, they developed a need for a dark period. In mature plants, an increase in the dark period from 0 to 4 hours (while maintaining an equal light sum) resulted in a production increase of 50% (Grimstad, 1990).

Sweet pepper

Seeds are sown in plug trays and a germination temperature of about 25°C is maintained for a week. When germination chambers are available, alternating temperatures can be given. For example, the application of 20°C for 16 hours followed by 30°C for 8 hours breaks the dormancy, which occasionally occurs in the seeds. After potting or transplanting (after about 2 weeks), the 24-hour average temperature is lowered to 21-22°C. Illuminated plants are bigger, firmer, with stronger flower buds and require a shorter growing period. For later planting during



Cucumber, together with melon, pickling cucumber and squash, belong to the family of the Cucurbitaceae.
The cucumber has unisexual flowers and is monoecious. Flower initiation is not daylength-sensitive, the sex-expression of the flowers of certain cultivars is. SD promotes the development of female flowers, while LD promotes male flowers. High light sums promote the development of female flowers whereas low light sums combined with high temperatures increase the number of male flowers. Current cultivars, however, only bear female flower.
Cucumber has a very high light requirement.

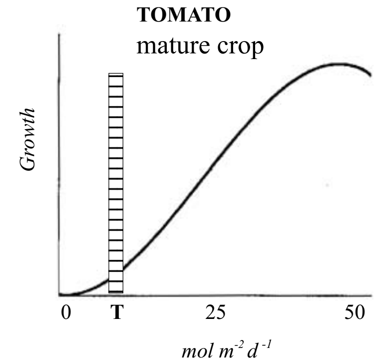


Sweet pepper belongs to the family of nightshades or Solanaceae.
They originate from Brazil and Central America.
The initiation of flower primordia is hardly affected by a photoperiod between 7 and 15 hours, while at 24 hours the initiation is delayed by 5-9 days.
Even though this is a quantitative short-day effect, the plant is generally referred to as daylength neutral. The number of leaves to the first flower is 8 to 10. High night temperatures delay or inhibit flowering.
A mature crop has a very high light requirement.

the season, lighting is often omitted because the flower buds are too vigorous. The percentage of splitting and the risk of an excessively first fruit set may increase due to the supplemental lighting.
The lighting period is usually between 16 and 18 hours, but 24 hours is possible.

Tomato

In lower latitude countries (<50°), tomato is grown successfully outdoors. The climatic conditions during winter season in these countries are much better with respect to light and temperature, compared to in The Netherlands. Excessively high temperatures, however, are detrimental, and limit the greenhouse production during the summer in those countries.



Tomato belongs to the family of nightshades or Solanaceae. The species originated from the coastal plains from Ecuador to Chile in South America. It was in Mexico, however, that the crop was domesticated for the production of tomatoes.

The plant has no distinct daylength sensitivity. The flower initiation is daylength neutral, developing autonomously, and not dependent on special environmental factors. Still these environmental factors exert a certain influence. At certain light sums flowering is stimulated by shorter days. For this reason the tomato is also referred to as a quantitative SD plant. The vegetative growth is promoted by long days.
The number of leaves below the first truss is reduced by high light sums and low temperatures.
*The target value (**T**) for adequate flower initiation is between 5-6 mol m^{-2} d^{-1}.*
A mature crop has a very high light requirement.

Effect of light sum

The light sum influences the number of leaves below the first truss (vegetative phase), the initiation of the truss and the number of flowers, the initiation rate of leaves and flower truss, the period from flower initiation to flowering and subsequently from fruit setting to harvest. In addition the quantity of light affects plant mass and fruit yield. When photosynthesis is not optimal, vegetative growth (leaves) takes priority over the generative growth (flower truss).

Light sum and temperature

The light sum and temperature during the low-light winter months should be balanced for the successful production of seedlings and young plants. Excessive temperatures under low-light conditions may lead to abortion of truss or flowers. When sufficient sugars are formed, a higher temperature strongly stimulates the development rate of the inflorescence. Proper adjustment of light and temperature makes it possible to obtain a quality plant with a carefully controlled plant mass and high quality flower trusses.

Light sum and truss development

The light sum plays a central role in the development of the flower trusses under different environment factors. Light determines the flowering rate and the quality of the first truss(es). Low light conditions can result in abortion of several flowers of the first truss (usually the last ones) or even the complete truss. This happens at a stage when the first truss is visible, 45 days after sowing under favorable light conditions. At this stage the truss has developed up to and including the petals, but not much further. Abortion occurs between 5-6 and 10-12 days after the truss started to appear (Kinet, 1977). During this period, the formation of pollen and ovules is in progress.

Light sum for seedling production

Favorable light levels for seedling production is 83 µmol m^{-2} s^{-1} during a photoperiod of 16-20 hours. This corresponds with a light sum of 4.8 to 6.0 mol m^{-2} d^{-1}. A level of 1.2 mol m^{-2} d^{-1} appeared to be too low (Kinet, 1977). This light sum for a period of 10 days causes abortion of the complete truss. Flower initiation starts in the fourth week after sowing as a result of a light sum of 4.8 mol m^{-2} d^{-1}. The truss is then visible 45 days after sowing. Two weeks later (about 2 months after sowing), flowering starts. Under less favorable conditions, the flower development is delayed or abortion takes place. If seeds are sown in October/November, flower development takes place in December, the darkest month of the year. If temperatures are too high in relation to the light sum, the flowers or the entire first truss aborts 5-9 days before flowering. Normally, this critical phase takes place during the first half of January with seeding done during October or November. Lowering the temperature to, for example, 16°C at low light levels during that critical phase can reduce the risk of abortion. When light is the limiting factor, nitrogen fertilization should be adjusted as well. Excessive nitrogen inhibits flower development and fruit set. Under high light conditions, a higher nitrogen concentration has the opposite effect.

Temperature and truss quality

Low temperatures at the beginning of truss initiation may cause split trusses and malformed flowers, with an increase in the number of petals, stamens, and locules in the ovary. Pollen production stops at temperatures below 10°C.

Plant mass
The plant mass of a tomato at the beginning of the cropping cycle determines the early and total yield. Additional light during the winter results in growth acceleration. Moreover, the plants remain more compact and are younger at the beginning of the cropping cycle than when they had been grown without supplemental lighting. Preferably, the first truss should develop on the tenth or eleventh leaf, especially for crops grown early in the heating season. More leaves result more photosynthesis, and that positively affects the quality of the first truss and the flowers. Not only light but also temperature determines the number of leaves below the truss. High temperatures increase the initiation rate of the leaves, so that more leaves develop below the first truss, while low temperatures reduce the initiation rate. The supplemental light level has an effect, since a high light sum decreases the number of leaves whereas a low light sum increases it.

Effects of lighting
Higher light sums also stimulate the growth of the root system, resulting in a decreased shoot/root dry matter ratio. Higher temperatures cause the opposite. It has been demonstrated that the light sum received by seedlings affects the earliness of the first harvest. When, after germination, seedlings were given supplemental lighting until 5 days before flowering of the first truss to a total light sum of 650 mol m^{-2}, the harvest of the first fruit followed after 100 days. Using a light sum of 950 mol m^{-2}, the harvest of the first fruit followed after 85 days (Janes et al., 1991).

Temperature control after sowing
The following temperature set points can be maintained after sowing: 25°C for the first 4-5 days, followed by 2 days at 21°C, and then 17-18°C. The final daily temperature should be maintained during further plant production. When the plug is transplanted into the final container, a slightly higher temperature is maintained for several days.

Lamp types
A variety of lamp types have been evaluated for supplemental lighting. The elongation of tomato plants is slightly stimulated by high-pressure sodium light, while fluorescent light and high-pressure mercury light with relatively high amounts of blue have an inhibiting effect on elongation. In comparison with natural light, a mixture of yellow and green light increases the leaf area slightly (Mortensen, 1987). Therefore, SON-T lamps are a good choice because of the large amount (40%) of yellow and green light.

Photoperiod
Although tomatoes are considered to be daylength neutral, they are still sensitive to various daylengths. At a long-day of 16 hours, growth is higher compared to a short-day of 8 hours, assuming that the light sum is the same in both situations. The daylength affects the distribution of dry matter in the plant. Under LD conditions, more sugars are transported to the leaves. SD conditions stimulate the generative growth, as well as quicker initiation of the flower truss.

The light intensity is represented as the Photosynthetically Active Radiation (PAR) in µmol m^{-2} s^{-1} (1 µmol m^{-2} s^{-1} corresponds with 6.023•10^{17} photons of light).
The daily light sum is the number of photons intercepted per m^2 per day, expressed in mol m^{-2} d^{-1}.
Radiation in terms of energy is expressed in watt m^{-2} or J m^{-2} s^{-1}, and the day sum in J cm^{-2} d^{-1}, either in total radiation (280-2,800 nm) or PAR (400-700 nm).

When seedlings are lighted for 24 hours, leaf damage develops over time, which may lead to plant necrosis and consequently death (Kristoffersen, 1963; Withrow, 1949; Arthur, 1930; and others). During plant production, this may result in disorders and accelerated senescence of the leaves. In addition, chlorosis, abnormal enlargement of the palisade mesophyll cells, modifications in the structure of plastids, and a slowing down of growth and flowering may develop (Globig, 1997).
High temperatures promote, while low temperatures reduce, the damage of lighting too long. Chlorosis is due to accumulation and inadequate translocation of starch and sugars.
For many cultivars, a dark period of less than 4 hours is detrimental. In practice, safe margins are observed, supported by research data (Germing, 1963; Klapwijk, 1986).
In The Netherlands, the dark period varies between 6 and 8 hours, in North America between 7 and 10 hours (Demers et al., 1998). However, tomatoes grown naturally under 24-hour lighting do not show any negative symptoms (*e.g.* during the summer in Alaska and Finland).

Final stages of crop production
The rate of photosynthesis of 8 to 9 week old tomato plants levels reaches saturation above light intensities of 500 µmol m^{-2} s^{-1} (with a CO_2 concentration of 1,850 ppm). This means that for optimal growth during the winter, supplemental lighting can be provided using high light levels (Lakso, 1984). From November to January the average light levels in the greenhouse do not exceed 200 µmol m^{-2} s^{-1}. In experiments in Quebec (47°N.L.) 100 µmol m^{-2} s^{-1} has been applied with great success (Section 6.2.7).

Converting instantaneous light levels and light sums

*For **high-pressure sodium** (SON-T Plus 400 W) light:*
1 µmol $m^{-2}s^{-1}$ = 85 lux = 0.2 Wm^{-2} PAR = 7.9 ft-c
Light sum using HPS
1 MJ m^{-2} PAR = 5 mol m^{-2} = 118 klxh = 10,970 ft-ch

*For **daylight**, the following conversion can be used:*
1 µmol $m^{-2}s^{-1}$ = 56 lux = 0.217 Wm^{-2} PAR = 5.2 ft-c
***Light sum** (45% PAR of total radiation)*
1 MJ m^{-2} PAR= 4.6 mol m^{-2} = 71.9 klxh = 6,640 ft-ch

6.2 Lighting Recommendations for Various Crops

6.2.3 Lighting of bedding plants

Introduction

Bedding plants can be classified in groups with an average, high, and very high light requirement. Plants with a high to very high light requirement can often endure some shade during part of the day.

Classification:

I. Sun plants have a **high to very high** light requirement of **20-50** mol m^{-2} d^{-1}.
Examples are:
Ageratum, Antirrhinum, Argyranthemum, Callistephus, Calendula, Celosia, Dahlia, Dianthus types, Gazania, Pelargonium Zonale hybrids (+ seed), Phlox, Petunia, Portulaca, Salvia, Tagetes types, Verbena, Vinca, Viola types and Zinnia.

II. Plants with an **average to high** light requirement of **10-30** mol m^{-2} d^{-1} can also be grown on somewhat shaded locations, for example:
Arabis, Aubrietia, Begonia semperflorens and tuberous hybrids, Campanula, Coleus, Fuchsia, Iberis, Impatiens, Lobelia, Myosotis, Pelargonium Peltatum hybrids, Primula, and Viola types.

Many bedding plants are sown during the low-light period of the winter for delivery in plug trays or seed flats from week 6 (middle of February) onwards. Supplemental lighting is needed to obtain uniform, compact plants with a strong root system.

Lighted seedlings have thicker leaves and higher plant mass; they are firmer, more vigorous, better branched and less susceptible to fungi and bacteria. Also, the percentage of germination increases. The plant weight doubles when the light sum is increased from 1.6 to 3.8 mol m^{-2} d^{-1}, as has been demonstrated at the Research Station in Aalsmeer, The Netherlands (Vogelezang, 1997). In addition, increasing the light sum and temperature can shorten the production period of many bedding plants. Lighting makes several crops a year possible, each crop grown under different daylength and photoperiodic conditions. The effect of lighting is closely related to the resulting increase in leaf area.

Daylength

For many bedding plants the length of the day and/or night period manipulates growth, development, and the time of flowering. There are short-day (SD), long-day (LD) and daylength neutral (DN) plants. For example, Petunia and Callistephus branch under SD conditions and remain compact while flowering is delayed. Under LD conditions, this growth pattern is reversed. The accompanying table provides a number of examples.

Tuberous begonias are given supplemental lighting after sowing in December to a daylength of at least 14 hours. A daylength of less than 12 hours results in less flowers and early tuber initialization. The development of bedding plants can be better controlled when the sensitivity to photoperiod is taken into account during plant production.

Juvenile phase

Some bedding plant varieties can only flower after a certain number of leaves have been formed. In other words, they must have completed a certain juvenile phase. This is the case for species like Antirrhinum, Callistephus, Gomphrena, Salvia, and others.

6.2.3 BEDDING PLANTS

PHOTOPERIODIC EFFECTS

Ageratum	LD	promotion of flowering
Antirrhinum	LD	promotion of flowering
Begonia semperflorens	DN/LD	flowering, cultivar dependent
Begonia tuberous hybrids	LD	tuber formation under SD
Callistephus	LD	elongation, flower induction
	SD	flower development
Celosia	SD	promotion of flowering
Centaurea cyanus	LD	elongation, flowering
Cleome	SD	promotion of flowering
Coleus	SD	promotion of flowering
Cosmos	SD	promotion of flowering
Dahlia	SD	promotion of flowering
Dianthus sinensis	LD	promotion of flowering
Gaillardia	LD	promotion of flowering
Gazania rigens	LD*	promotion of flowering
Gomphrena	SD	promotion of flowering
Helianthus	SD	promotion of flowering
Impatiens	SD	critical daylength 15,5 h
Lavatera	LD*	promotion of flowering
Lobelia	LD*/DN	flowering, cultivar dependent
Nicotiana	DN	flowering not effected
Nigella	LD*	promotion of flowering
Papaver rhoeas	DN	flowering not effected
Petunia	LD	promotion of flowering
Phlox	LD	promotion of flowering
Salpiglossus	LD	promotion of flowering
Salvia	SD/DN/LD	flowering, cultivar dependent
Scabiosa	LD	elongation, flowering
Tagetes erecta	SD/DN/LD	flowering, cultivar dependent
Tagetes patula	DN	flowering not effected
Verbena	LD	promotion of flowering
Vinca	DN	high temp., stim. flowering
Viola	DN/LD	flowering, cultivar dependent
Zinnia	SD	promotion of flowering

LD=long-day, SD=short-day, DN=daylength neutral

The long-day and short-day plants show quantitative or obligate responses to the daylength.*

By selection, cultivars can be developed that respond differently to daylength than indicated above.

Light and dark germinators

Some plants require light for germination, while others only germinate in the dark. Examples of the first group are: Antirrhinum (snapdragon), Begonia, Celosia, Coleus, seed geranium, Impatiens, Matthiola, Petunia and Salvia. The following plants germinate in the dark: Calendula, Dahlia, Delphinium, Gazania, Nemesia, Papaver, annual Phlox, Tagetes, Tropaeolum, Verbena, and Viola. Large seeded plants tend to require darkness, while small seeds tend to be red light responsive.

Germination

Plants requiring light during germination are not covered after sowing. Red light is required for germination and this can be provided by high-pressure sodium lamps. For the germination itself a low light intensity is needed. But when the light intensity is too low after germination, elongated seedlings may develop. On average, a supplemental light intensity of 65 μmol m^{-2} s^{-1} is recommended, and 240 μmol m^{-2} s^{-1} in germination rooms (Koranski, 1983). During germination, a 24-hour daylength is possible. The advantage of using a high light level is that a high germination temperature can be maintained as well. For optimal germination most bedding plants require (in addition to a high RH) a temperature of 21 to 24°C. Some need higher, others lower temperatures. The desired sowing conditions vary strongly and should be determined for each crop separately. Some examples are (Nau, 1993; Dole, 1999): (without cover) Salvia officinalis 24-25°C, Petunia 24-26°C, Begonia semperflorens 26-27°C, Ageratum 26-28°C. Because supplemental lighting can be compared to radiant heaters, they can be used effectively to obtain the desired temperatures. For lettuce, the light requirement for germination disappears when the temperature is kept below 23°C (Hartmann, 1997).

Production of bedding plants

After germination plants reach the following developmental stages (stages 2 – 4), each of which requiring its own environmental conditions. Temperature and RH requirements gradually decline. Particularly after emergence, special attention is needed to prevent burning of the tender seedlings.

Ageratum / Antirrhinum / Pelargonium / Petunia

Lighting of seed geranium, Ageratum and Antirrhinum for 12 hour a day with for example a light intensity of 30 μmol m^{-2} s^{-1} after sowing in January, shortens the production period by 20-30%. Additional benefits of 10 to 15% can be obtained with a higher light intensity of 60 μmol m^{-2} s^{-1} for 20 hours (Hendriks, 1993). Higher light sums accelerate flowering. In Petunia, growth and development are accelerated by increasing light intensities to about 700 μmol m^{-2} s^{-1} (Horn, 1996). Ageratum, Antirrhinum and Petunia are LD plants of which flowering can be accelerated by extending the daylength. In Petunia this can also be done with higher daily average temperatures. Petunias grown in hanging baskets under natural conditions initiate flower buds from mid-March onwards. The critical daylength is 14.4 hours for the cultivar 'Express Blush Pink'. Longer photoperiods have no beneficial effects (Adams, 1998). For flowering of the small-flowered cultivars 'Million Bells' and 'Carillion', 6 weeks of lighting is necessary at the beginning of April with a minimum light sum of 3.4 mol m^{-2} d^{-1}. Under controlled growing conditions (18 hours at light intensities of 100 and 200 μmol m^{-2} s^{-1}) Petunias appeared to start flowering at a light sum of 13 mol m^{-2} d^{-1} and average temperatures of 15 to 20°C after 74 and 56 days, which is 15 and 11 days earlier, respectively, compared to the 6.5 mol m^{-2} d^{-1} treatment (Kaczperski, 1991).

Dianthus and Gazania

Many bedding plants and summer flowers can be forced to flower by the end of April when using supplemental lighting. For Gazania hybrids and Dianthus chinensis, for example, a shortening of the production period by 2 to 5 weeks using a light intensity of 50 μmol m^{-2} s^{-1} (HPS, SON-T Plus) can be obtained. In Dianthus additional flowering lateral shoots develop: 4.9 instead of 1.7 (Hendriks, 1993). For a tripling of the number of sidebreaks, Gazania needs more light: 60 μmol m^{-2} s^{-1}. In general, 35-50 μmol m^{-2} s^{-1} is recommended, which should be continued until mid-March. The lighting period varies from 15-16 hours in December to 3 hours in March.

Elongation and lighting

For some plants, supplemental lighting during the daytime is better to prevent excessive elongation. Frequently these plants are LD-plants, such as Petunia, that remain short under SD but make long, non-branched straight stems under LD, particularly under photoperiods longer than 12 hours. If necessary stem elongation can be controlled further by the application of negative DIF (De Graaf, 1989). Higher light levels do not change this effect.

Germination and seedling production of plugs

Germination and seedling development can be subdivided into 4 stages:

1. *Germination of the seed and the emergence of the tap root*
2. *Development of the root system and development of cotyledons*
3. *Development of the first true leaf*
4. *Seedling growth up until it is ready for transplant*

The environmental conditions are usually adjusted during each stage, for example (Ball, 1991a):

Impatiens walleriana

1. *24-27°C, 90 μmol m^{-2} s^{-1} PAR, 100% RH, no fertilization;*
2. *22-24°C, 90 μmol m^{-2} s^{-1} PAR, 75% RH, liquid feed at 50-100 ppm N with 20-10-20, once a week;*
3. *18-21°C, liquid feed at 100-150 ppm N with 20-10-20, once a week;*
4. *16-17°C, liquid feed as required.*

The light sum is a determining factor for germination. Germination takes two days under continuous lighting at a light intensity of 20 μmol m^{-2} s^{-1}, or one day at continuous lighting at 100 μmol m^{-2} s^{-1}. As soon as the root starts to elongate, continuous lighting should be stopped.

6.2 Lighting Recommendations for Various Crops

6.2.4 Lighting of foliage plants

Introduction

Supplemental lighting is frequently used in propagation, for the stimulation of cutting production as well as rooting. But also during cropping, supplemental lighting can reduce the production period and improve quality. After mid-February, the ambient light strongly increases both in daylength and intensity, which results in the general opinion that supplemental lighting is only useful in the period from mid-October to mid-February.

As plants get bigger and take up more space, the economic advantages of lighting are gradually diminishing. With large plants such as Ficus benjamina, supplemental lighting is frequently applied during the rooting of cuttings and in the pot-to-pot stage before spacing. In subsequent phases, supplemental lighting is not applied, despite the potential acceleration of development and improved plant form. However, large plants such as some palm species (*e.g.* Beaucarnia and Areca) do benefit from supplemental lighting. Yucca, one of the most common grown pot plants, hardly responds to supplemental lighting. Ferns do show some response, especially the smaller types, and supplemental lighting is often applied during propagation.

Arguments in favor of supplemental lighting are:

- Increased rate of development;
- Improvement of quality and keeping quality;
- Higher market prices;
- Fewer climatic problems due to a lower RH;
- Reduced plant losses;
- Labor requirements and crop scheduling are more evenly distributed throughout the year.

Classification

Foliage plants show large differences in light requirement, from very high to low:

I. **Very high light**: **30-50** mol m^{-2} d^{-1}:
Codiaeum, Ficus-types such as Ficus benjamina and Ficus elastica, Schefflera, Yucca

II. **High light:** **20-30** mol m^{-2} d^{-1}:
Dracaena fragrans/marginata, Radermachera

III. **Average light**: **10-20** mol m^{-2} d^{-1}:
Coconut palm, Cordyline, Dieffenbachia, Dracaena deremensis, Epipremnum, Fatshedera, Hedera, Howeia, Nephrolepis, Syngonium

IV. **Low light**: **5-10** mol m^{-2} d^{-1}:
Adiantum, Aglaonema, Aphelandra, Calathea, Maranta, Pilea, Platycerium, Pteris.

This classification according to light requirement is based on optimal light sums (see also Table 6.1). One should keep in mind that this classification is rather general. Within one genus, large differences between species and cultivars can occur. Also the size of the plants, the season, and the cultivation method play a role.

For the various plant species discussed in this section, a graph is included showing the relationship between plant growth and required light sum. Using these graphs, it can be determined whether the use of supplemental lighting will lead to improved plant growth. If for example, lighting is provided at: 40 µmol m^{-2} s^{-1} for 14 hours, the plants receive an extra light sum of 2 mol m^{-2} d^{-1}. If the required light sum for optimum growth is 20 mol m^{-2} d^{-1}, and the plants received 2 mol m^{-2} d^{-1} of natural light, then it is obvious that the total light sum of 4 mol m^{-2} d^{-1} (2+2) is far still far short of the optimum. Despite the low light sum, using supplemental lighting can have significant advantages.

Photoperiodic sensitivity of foliage plants

Many foliage plants come from tropical areas with high temperatures. They grow in the shade forests, as well as in full sun (Ficus types). As yet, there is not much information on the photoperiod sensitivity. Many of the plants mentioned belong to one of the following families:

***Agavaceae:** Cordyline, Dracaena, Yucca. For flowering they need a minimal number of leaves. They all have a terminal inflorescence. They are likely SD plants or flower at lower temperatures.*

***Araceae**: Dieffenbachia, Epipremnum, Syngonium. For flowering the crop should be sufficiently developed. It does not appear that these plants are photoperiod sensitive but often require a high temperature to flower.*

***Araliaceae**: Aralia, Fatshedera, Hedera, Schefflera. Mature Hedera plants flower very late in the season (September). It probably is a LD plant.*

***Marantaceae**: Calathea, Maranta.*

Calathea needs SD for flowering. The optimal temperatures are between 18 and 20°C.

Table 6.5. ***Effect of installed lamp wattage on the production period and plant size of foliage plants based on research data collected from various greenhouse operations.*** *For lamps, the SON-T 400 W bulbs were used. Source: Oprel, 1989.*

	Installed wattage m^2/lamp	light intensity $\mu mol\ m^{-2}\ s^{-1}$	production time (wks) winter	production time (%) summer	increase in prod. winter (%)	plant size (%) winter	increase (%) in plant size winter
Codiaeum 'Excellent'	13	40	26.8	62.6	16	85	9
Dieffenbachia 'Compacta'	15	35	23.5	68.8	16	82	15
Ficus benjamina 'Exotica'	15	35	30.6	77.8	6	68	25
Nephrolepis 'Teddy Junior'	16	33	23.4	79.5	9	58	28
Schefflera 'Compacta'	12	45	26.2	63.8	17	78	23

The effect of extra light in the winter months is demonstrated by for example:

- Increased leaf initiation;
- Increased axillary (side-)shoot formation;
- Reduced production period;
- Increased plant height;
- Improved color and mass.

Leaf initiation

An increase in the daily light sum under ambient light conditions in a greenhouse in The Netherlands from December to March accelerated leaf formation in Ficus with 100%.

Axillary shoot formation

The number of laterals in Ficus also increased with 40% during the period from December to March. This is positive for cutting production. For this reason stock plants of Dieffenbachia and Ficus are frequently illuminated. Limited lighting with 1.7 to 2.1 $mol\ m^{-2}\ d^{-1}$ for low light requiring plants (*e.g.* Maranta) already promotes branching considerably, while the leaf initiation rate remains the same. Table 6.5 shows the effects of supplemental lighting in various greenhouse operations on plant size. It is evident that the winter crop quality is improved significantly. The plant size shows a moderate increase (9-15%) for Codiaeum and Dieffenbachia, while it increases strongly with more than 20% for Ficus, Nephrolepis and Scheffleră. Still, the lighting capacities for Ficus and Nephrolepis do not seem to be optimal yet, which is even further evident from the acceleration of the production time.

Production time

A significant reduction in the production time is shown for three crops in particular: Schefflera, Dieffenbachia and Codiaeum (Table 6.5). The supplemental light sums, however, are not sufficient to obtain the developmental rates during the summer. The developmental rates of Fatshedera and Hedera are also closely related to the installed capacity of the supplemental lighting system.

Plant height

For the species mentioned in Table 6.5, plant height is stimulated through lighting. Fatshedera responds most favorably to 30 $\mu mol\ m^{-2}\ s^{-1}$ and a photoperiod of 20 hours during the period from September to March. The longer the photoperiod, the taller the plants grow. This is caused by higher growth rates (more leaves) and slightly larger internode lengths for crops grown during the period between December and March.

Color

The effect of supplemental lighting on the leaf color is relatively significant for Cordyline, Dieffenbachia and Schefflera, moderate for Codiaeum and small for Ficus.

The variegated Dracaena may become yellow, and should therefore not be lighted according to standard practices. The light spectrum plays an important role, because at high sunlight intensities yellowing is not observed. Applying a photoperiod of more than 15 hours leads to greening of the white parts of Dieffenbachia 'Camilla', while for 'Compacta' this happens when lighting is extended past 18 hours (De Beer, 1992).

Plant mass

The Dieffenbachia cultivars mentioned above become heavier and sturdier as a result of supplemental lighting. The fresh mass after 16 weeks was twice as high compared to control plants. The shoot mass and the number of shoots increased.

Daylength

To avoid damage (leaf drop, necrosis, yellowing) it is recommended, especially for crops with a low light requirement, to combine a lower light intensity with a longer lighting period. Cordyline is less prone to stress at a photoperiod of 16 hours compared to 18 hours (Balemans, 1991). Ficus benjamina can endure 24-hour photoperiods. Thus a lower, continuous lower light intensity may be chosen: 35 $\mu mol\ m^{-2}\ s^{-1}$ for 24 hours instead of 70 $\mu mol\ m^{-2}\ s^{-1}$ for 12 hours. The latter strategy can be applied for lighting of two separate greenhouse compartments successively, where lamps are moved from one compartment to the other each 12 hours. Leaf yellowing can be reduced by keeping the temperature at a minimum of 20°C. Ficus plants grown with supplemental lighting do not suffer a loss of quality when placed in low-light living rooms.

Lighting recommendations per crop

For a number of important crops lighting recommendations are presented.

Cissus rhombifolia 'Ellen Danica'

Supplemental lighting at an intensity of 45 μmol m^{-2} s^{-1} for 16 hours per day reduced (during the winter months) production time by 4 to 6 weeks compared to a production time of 15 weeks under ambient conditions. The lamps were switched off as soon as levels of more than 10 W m^{-2} are measured outside the greenhouse (Verberkt, 1988).

Codiaeum variegatum

Croton has a very high light requirement and can be grown at very high light levels (Table 6.6). A moderate additional amount of light during the winter was sufficient to improve firmness and color (using a daylength of 18 hours and a supplemental lighting intensity of 30 μmol m^{-2} s^{-1}). This resulted in an increase of fresh and dry mass as well as a slight increase in internode length. Switching the lamps on and off was done at an intensity of 50 W m^{-2} of global outside radiation. Lighting in combination with soil heating (root temperature at 27°C) reduces quality (Verberkt, 1990). However, lighting improved the variegation of the leaves.

In another experiment with the cultivar 'Gold Sun' and with a supplemental light intensity of 45 μmol m^{-2} s^{-1} during the winter months, plant height was increased by 40% after 100 days without affecting quality (Verberkt, 1988). During this period, the fresh mass was more than 60% higher compared to the plants grown at ambient conditions. Compared to unlit plants, the variegation of illuminated plants was improved while leaves were larger. Therefore, supplemental lighting of stock plants should be beneficial for uniform leaf development. High supplemental light intensities are recommended (Table 6.5).

Cordyline fruticosa

This shade plant grows in humid forests. It prefers a shaded habitat but a little direct sunlight is allowable (Griffith, 1998). This plant does not obtain the desired red coloring during the winter months, so supplemental lighting is required for a good quality. A dark period of 8 hours is necessary to avoid stress (Balemans, 1991). Supplemental lighting is provided at an intensity of 30 μmol m^{-2} s^{-1}, which is rather low compared to the optimal conditions (Table 6.6).

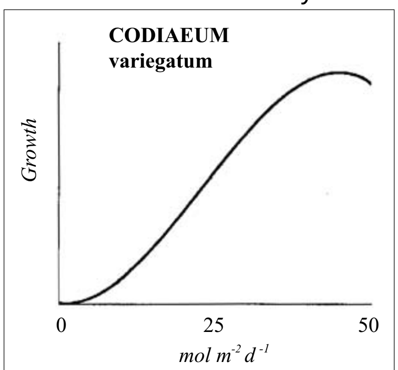
Dieffenbachia maculata

Greenhouse growers frequently use a light intensity of 35 μmol m^{-2} s^{-1} (Table 6.5). If the photoperiod exceeds 18 hours, the white of the leaves of the cultivar 'Compacta' become green. For the cultivar 'Camilla', this happens at photoperiods beyond 15 hours (De Beer, 1992). Lighting on Dieffenbachia increases the number of shoots, which are also heavier and slightly longer, as well as the fresh mass, while the production time is reduced (Table 6.5). The number of leaves changes are not affected by longer photoperiods compared to *e.g.* Ficus benjamina. In an experiment with the cultivar Dieffenbachia maculata 'Picturata', doubling the light sum in December resulted in 20% more shoots and leaves. High light levels (120 μmol m^{-2} s^{-1}) during 24-hour photoperiods caused severe chlorosis along the leaf margins, which disappeared when shorter photoperiods were maintained (16 hours) and the light intensity was reduced to 60 μmol m^{-2} s^{-1}. The daily light sum (including natural light) remained at 6 mol m^{-2} d^{-1}. Lighting should be accompanied by corresponding optimal temperatures of 24-25°C.

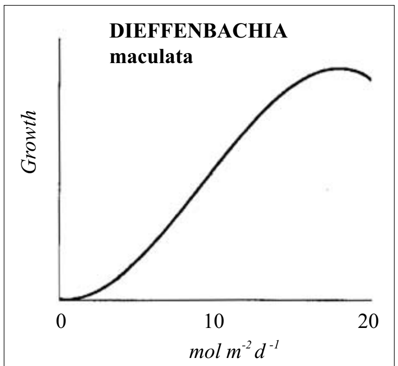
Dracaena deremensis and marginata

The cultivars grown in The Netherlands originate from tropical Africa. They cannot endure too much light. Dracaena deremensis cultivars should be shaded at outside global radiation levels above 275 W m^{-2} (DLV, 1997/98). This prevents the leaf color from becoming too pale. Dracaena marginata can be grown at higher light intensities.Shading should be started at outside global radiation levels of 325 W m^{-2} or 400 μmol m^{-2} s^{-1} inside the greenhouse (DLV, 1997/98).

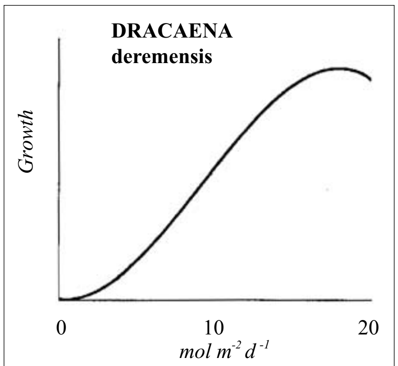
Light levels above 350 W m^{-2} may cause desiccated leaf tips. Based on these light levels and the data presented in Table 6.6, supplemental lighting during the period from October to early March with 40 μmol m^{-2} s^{-1} is feasible. In December, for instance, the av-



Codiaeum or Croton belongs to the family of Euphorbiaceae is a native of tropical Asia. For a good leaf color it needs a lot of light. The light requirement is very high.



Dieffenbachia is a green perennial from tropical South America with an average light requirement.



This genus belongs to the family of Agavaceae. Dracaena deremensis has an average, while Dracaena fragrans and marginata have high light requirements.

erage light level in the greenhouse does not exceed 180 µmol m^{-2} s^{-1}. Lighting in winter, however, may lead to yellowing in the variegated Dracaena cultivars.

Epipremnum pinnatum

This plant can be grown at light intensities ranging from 200 to 800 µmol m^{-2} s^{-1} (Table 6.6). Supplemental lighting to a photoperiod of 18 hours and an intensity of 30 µmol m^{-2} s^{-1} was not always optimal (Verberkt, 1990b). Additional light intensity increases the fresh and dry mass as well as internode length. This could led to overly tall plants. The leaves become bumpy, rather hard and tough. In one of the first lighting experiments with and without bench heating, plants with bench heating (27°C substrate temperature) were rated the best, but in a second experiment the internodes were too long. A maximum photoperiod of 14 hours is recommended. The effects of the high root zone temperatures are under investigation.

Fatshedera lizei / Hedera canariensis

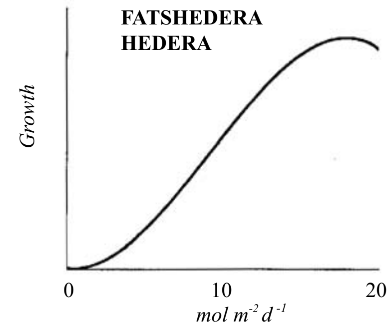
From September through March, a light intensity of 30 µmol m^{-2} s^{-1} and a photoperiod of 20 hours were found to be optimal (Verberkt, 1990). The longer the photoperiod, the taller the plants. This effect was due to an increased growth rate as well as a slightly extended internode length. A photoperiod of 24 hours resulted in sturdy plants with a thick stem and big leaves. During another wintertime experiment with a light intensity of 45 µmol m^{-2} s^{-1} and a photoperiod of up to 16 hours, there was a significant effect on plant height. After 16 weeks the plant height was almost twice as high compared to the control treatment, and production time could be shortened by 50%. The fresh mass after 16 weeks was more than 70% higher compared to the control plants (Verberkt, 1988). These positive results were also obtained with Hedera canariensis 'Variegata'.

Ferns (Adiantum, Nephrolepis, Pteris)

Seeds (spores) of ferns require light for germination. A light intensity of 35 µmol m^{-2} s^{-1} is required (DLV, 1992). Supplemental lighting with a 16-hour photoperiod shortens the time between germination and re-spacing by 2-3 weeks, and results in a more uniform emergence and a higher germination percentage. From re-spacing till potting, supplemental lighting is usually also provided. In commercial greenhouses, a light intensity of 30-35 µmol m^{-2} s^{-1} is used, for a minimum duration of 4 to 8 h (DLV, 1992). A light intensity of 50 µmol m^{-2} s^{-1}, however, would be better (Horn, 1996).

Adiantum spp.

A maximum photoperiod of 16 hours is recommended for Adiantum spp. Beyond this photoperiod, leaf necrosis develops and the development of the root system is delayed (DLV, 1992). The lamps are usually turned off at an outside global radiation level of 50-100 W m^{-2}. For the cultivation of the smaller types of fern (Adiantum and Platycerium) supplemental lighting is applied in this way. For the more sizable types

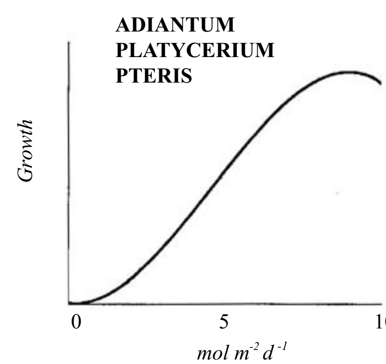


Fatshedera is the result of a cross between Fatsia japonica and Hedera helix and has an average light requirement.

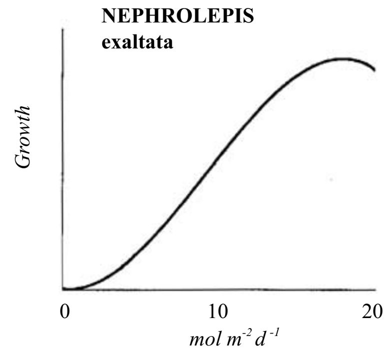
such as Asplenium and Nephrolepis lighting is usually limited to the first phase of cultivation when the pots are spaced pot-to-pot. But as discussed earlier, positive results are predicted when lighting is provided throughout the production cycle (DLV, 1992). During the winter months, ferns usually receive too little light. The greenhouse glazing should be as clean as possible to allow maximum light transmission. In spring and summer, however, shading is needed. When in February, the global outside radiation reaches an intensity of 225 W m^{-2} (approximately 275 µmol m^{-2} s^{-1} inside the greenhouse), it may become necessary to shade with an automatic shading system (DLV, 1992). During the summer, the set point for shade curtain operation is set between 300 and 350 W m^{-2} because the plants are less sensitive compared to during the winter.

Nephrolepis exaltata

Experiments with Nephrolepis cultivars 'Teddy Junior' and 'Boston' have demonstrated that a supplemental lighting period of 20 hours and a light intensity of 45 µmol m^{-2} s^{-1} provided the best results (Verberkt, 1995). A photoperiod of 24 hours resulted in mild chlorosis in 'Boston'. The fresh plant mass increased with lighting duration and intensity. Supplemental lighting for 16 weeks resulted in a doubling in fresh mass compared to unlit plants (De Beer, 1992). The



These ferns have a low light requirement. They should be shaded against direct sunlight with a high intensity (from mid-February onwards). Most of these ferns are epiphytes.



In contrast to other ferns Nephrolepis is grown under high light levels to obtain compact bushy plants. It has an average light requirement.

dry mass increased only with increasing light intensity. The higher the light sum (lighting period and/or higher intensity), the better the compactness, color, firmness, shoot formation, bushiness, and overall quality (Verberkt, 1995). In addition, the leaves started to curl more. During summertime, automatic shading was applied when outside global radiation levels exceed 400 W m^{-2}(corresponding with approximately 500 μmol m^{-2} s^{-1} inside the greenhouse) to avoid excessive leaf temperatures (DLV, 1991). Also, high light intensities caused lighter leaf colors and an overly compact growth (DLV, 1994). Therefore, this fern is usually grown under high light conditions. During the summer, some whitewash combined with a movable shade system provides optimal results. These aforementioned results point out that there is room for high-intensity lighting. In Nephrolepis, the rhizome formation during winter is stimulated when a supplemental light intensity of 35 μmol m^{-2} s^{-1} is provided. Therefore, year-round production of runners is feasible, which was impossible in the past (DLV, 1991). The profitability of using more light or increasing the lighting duration increases with an increased growing temperature.

Pteris cretica

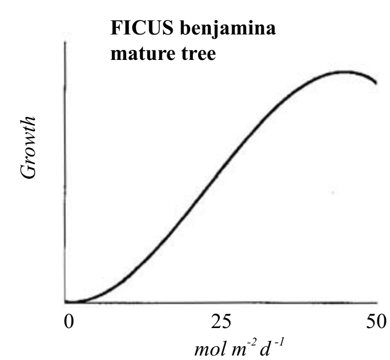
For Pteris cretica 'Albolineata', plant height, fresh and dry mass and percent dry matter increased with supplemental lighting using a 18-hour photoperiod and a light intensity of 30 μmol m^{-2} s^{-1}. However, the overall quality of lit plants was less than that of unlit control plants (Research Station for Floriculture and Glasshouse Vegetables in Aalsmeer, The Netherlands). The lit plants were too leggy and weak, while leaves and petioles were too big.

Ficus benjamina

This plant can endure high levels of sunlight (maximum outside: 600 W m^{-2} global radiation, (J.C. Bakker, 1995b). In a greenhouse (with 60% transmission), this corresponds with 162 W m^{-2} PAR or 745 μmol m^{-2} s^{-1}, which occurs in The Netherlands during the months of June and July only. The outdoor value of 600 W m^{-2} is mainly used as a starting point for shading. Even lower values are used for the variegated types because of the increased risk of sunscald (DLV, 1994). However, these plants can be grown at even higher light intensities (Table 6.6). The effect of supplemental lighting depended on the daily light sum (Terhell, 1992). As a result, growth increased in proportion to the amount of supplemental light provided during the winter season. The advantages were an acceleration of the production (4 to 6 weeks, during the period December-April), improved branching, and increased plant size and leaf area. Variegated cultivars can now be grown with reasonable success (Hendriks, 1993). Supplemental lighting with a light intensity of 45 μmol m^{-2} s^{-1} at plant height for up to 16 hours a day is useful during rooting and general plant production. After two weeks, the root system was found to be bigger compared to that of unlit cuttings. A slightly higher root zone temperature (+1.5ºC) due to the supplemental lighting may have caused this. The lamps were switched off when the outdoor light level measured exceeded 10 W m^{-2}. During a similar experiment with the cultivar 'Starlight' branching and lateral shoot production increased significantly due to the supplemental lighting, while fresh mass was 50% higher after 16 weeks compared to the control plants (Verberkt, 1988).

In another experiment with a supplemental light intensity of 30 μmol m^{-2} s^{-1} and a photoperiod of up to18 hours, the fresh mass of the cultivar 'Exotica' after 24 weeks had increased with 74% and with 86% for the variegated cultivar 'Starlight' compared to unlit plants (Verberkt, 1989). Lighting intensities of 30-45 μmol m^{-2} s^{-1} during the winter are too low to obtain the same amount of variegation as experienced during the summer. Therefore, plants show differences in variegation when summer cuttings are used as starting material in the fall.

Norwegian experiments indicated that this Ficus cultivar responded well to photoperiods of 24 hours based on the increase in number of leaves and dry mass (Mortensen, 1992a,b). Increasing the light intensity from 60 to 120 μmol m^{-2} s^{-1} increased dry matter by 27%, number of leaves by 33%, and plant height by 21%. Other supplemental lighting experiments showed that a dark period of 8 hours resulted in im-



This Ficus, that may reach a height of 18 m, is indigenous to India and Malaysia. It grows under very high light levels, but adapts remarkably to low light conditions.

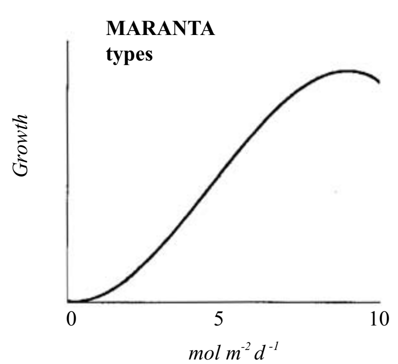
proved length and number of laterals. In addition, dry matter production increased at a light intensity of 40 μmol m^{-2} s^{-1}. As the length of the dark period decreased, the plants became taller (Beel, 1997).

Ficus elastica

Supplemental lighting has similar benefits on Ficus elastica 'Robusta' compared with Ficus benjamina. An increase of the light sum results in an increase of the number of leaves, dry mass, and stem length. Higher light intensities increase plant height, irrespective of the photoperiod. By increasing the photoperiod from 16 to 24 hours, the ratio between the dry mass of the leaves and the stem is reduced. Increasing the lighting intensity, however, does not change this ratio. For this Ficus cultivar, a 24-hour photoperiod is not optimal. Supplemental lighting during winter for 20 hours and a light intensity of 60 μmol m^{-2} s^{-1} was found to be optimal (Mortensen, 1990a). The increases in dry mass, numbers of leaves, and plant height using a 20 hour photoperiod are 23%, 8% and 7%, respectively, compared to a 16 hour photoperiod. The total daily light sum (supplemental plus sunlight) was maintained at 7 mol m^{-2} d^{-1}.

Hedera canariensis 'Variegata'

Research has shown that extra light during the winter months can shorten the production time considerably. Supplemental lighting of up to 16 hours a day with an intensity of 45 μmol m^{-2} s^{-1} at plant height resulted in a reduction of the production time by 4 to 6 weeks on a total production time of 15 weeks. The lamps were turned off when the outdoor light intensity exceeded 10 W m^{-2}. The plant height increased strongly, partly due to a somewhat larger internode length. This does not result in a reduction of overall plant quality. The production time was reduced by 50%, because plant quality is partly determined by plant height. The fresh weight after 16 weeks was twice that of unlit plants. In addition the plants were firmer, the leaves more variegated with larger surface areas. In addition, supplemental lighting improved the rooting of cuttings during the winter months.



Maranta originates from Brazil and has a low light requirement.

Maranta spp.

This shade plant does not require much light, just like *e.g.* Aglaonema and Calathea. At an inside light intensity of 250 and 450 μmol m^{-2} s^{-1}, automatic shading was applied (DLV, 1995). Supplemental lighting with 30 μmol m^{-2} s^{-1} and a photoperiod of 15-18 hours primarily promoted branching (Hendriks, 1993).

Palm

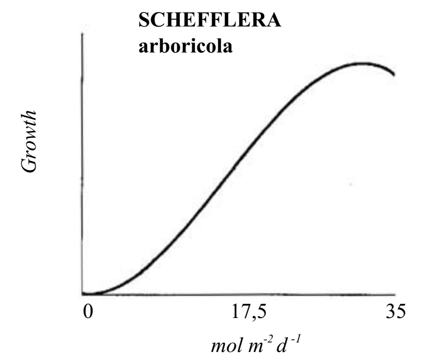
This group includes Areca, Beaucarnia, coconut palm and Howeia. The production time is only marginally affected by supplemental lighting during the winter. Palms are grown under heavy shade during the summer. When the leaves turn yellow, the light level in the greenhouse is usually too high. For coconut palm and Howeia, shading is applied at an outside global radiation of 170 and 200 W m^{-2} (approximately 210 and 250 μmol m^{-2} s^{-1}) respectively, or at 300 μmol m^{-2} s^{-1} as a general guideline (DLV, 1995). In case whitewash has been applied to the greenhouse, the critical light intensity for Howeia for closing the shade curtain is increased to 300-350 W m^{-2}. In The Netherlands, the average light intensity in December does not exceed 180 μmol m^{-2} s^{-1}. Using the maximum of 250-300 μmol m^{-2} s^{-1}, an additional 70-120 μmol m^{-2} s^{-1} can be provided during daytime. Growth and development can be further improved with supplemental lighting during the nighttime.

Radermachera sinica

As in Ficus benjamina, an increase in the photoperiod from 16 to 24 hours results in a significant increase of dry matter production (30%), under both low and high light intensities. The number of leaves increases, as well as plant height (26%). Plant height is not affected by a doubling of the light intensity. In Norwegian experiments, light intensities of 60 and 120 μmol m^{-2} s^{-1} were applied. But using a 24-hour photoperiod and the higher light intensity, severe chlorosis developed along the leaf margins, which disappeared using shorter photoperiods and lower light intensities (Mortensen, 1990a).

Schefflera arboricola

Lighting with an intensity of 30 μmol m^{-2} s^{-1} and 18-hour photoperiod has shown to be beneficial to the cultivars 'Compacta' and 'Gold Capella'.
Six hours after sunset the lights were turned on and once the outside light intensity reached a level above 20 W m^{-2}, they are switched off (Verberkt, 1989). The results were growth acceleration and an increase of fresh and dry mass and plant height. The latter was most significant during the period of week 48-52 (+130%), but in March the average increase was still 17%. The average internode length also increased: from 2.5 to 2.8 cm for the cultivar 'Compacta' and from 2.0 to 2.3 cm for the cultivar 'Gold Capella'. The fresh mass of the stems and leaves combined increased, with 50 and 25%, respectively. The plants got heavier and sturdier. The variegation of 'Gold Capella' during winter production was improved. The



This shrub or tree, which may reach a height of 5 m, belongs to the family of Araliaceae. The light requirement is very high.

conclusion was that during the winter months Scheffera, which is normally grows slowly, benefits considerably from supplemental lighting. The quality of the cultivar 'Compacta' was reduced under supplemental lighting, due to the increase in internode length. This could be overcome with negative DIF.

Syngonium podophyllum

Supplemental lighting during an 18-hour photoperiod and with an intensity of 30 µmol m^{-2} s^{-1} is not optimal (Verberkt, 1990a). Long shoots developed with long internodes and small green leaves. The number of shoots increased. Norwegian experiments tested higher light intensities (60-120 µmol m^{-2} s^{-1}) and 16 to 24-hour photoperiods (Mortensen, 1990a). Increasing the light sums from 6 to 13 mol m^{-2} d^{-1}(including ambient light) resulted in increases in the dry mass, the number and length of leaves. However, the plants were taller under a 20-hour photoperiod compared to a 24-hour photoperiod.

Yucca elephantipes

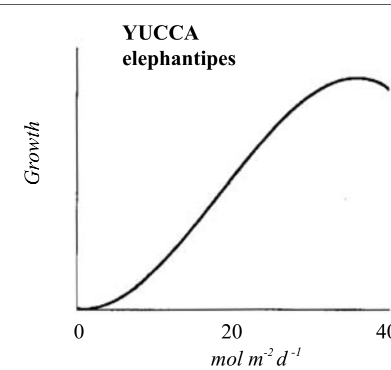
This species originates from the mountainous regions of Central America. The species grown in The Netherlands, elephantipes, is cultivated under rather low light intensities during summer. At outside global radiation levels above 375 W m^{-2} (corresponding with approximately 465 µmol m^{-2} s^{-1} inside the greenhouse), shade curtains are used. Supplemental lighting is not practical during the winter according to growers (Verdegaal, 1992). The light intensities they tested were probably too low. From November to January, the light intensities inside the greenhouse do not exceed 200 µmol m^{-2} s^{-1}, which is 265 µmol m^{-2} s^{-1} below the value used to start shading! It was found that the red light of high-pressure sodium lamps promotes the outgrowth of axillary buds. It is therefore useful to test higher supplemental light intensities for the production of Yucca, *e.g.* 75-100 µmol m^{-2} s^{-1}.

Lighting recommendations

Table 6.6 shows lighting recommendations based on both European and American research. Many of the American recommendations are derived from research conducted by Poole and Conover. However, large differences can be observed between the various recommendations. The values determined in Florida (column 3) resemble those used in The Netherlands. Florida (27°N), however, is located much further down South compared to The Netherlands (52°N). Comparison of the recommended light intensities makes it clear that even in The Netherlands there is much research left to be done in order to determine the optimum light intensities.

The recommended light intensities used in The Netherlands are derived from the outside global radiation data (in W m^{-2}) at which shading is recommended. The accompanying light intensities at crop level (µmol m^{-2} s^{-1}) are not very well known, just like the interactions of the optimum light intensity with other environment parameters.

Flowering pot plants and cut flowers are usually grown under high light conditions, in order to improve both production (increase dry matter and reduce production time) and keeping quality. For foliage plants, the situation is often different. They are grown for an extended period of time in a somewhat dark environment. For example, to avoid leaf abortion, plants should be grown under low light levels during the entire production process (acclimatization). Growers of foliage plants have to find a compromise between production and quality. Much more production information is needed. The minimum light intensities needed to keep the plants in optimum condition once they reach the ultimate customer are often based on experience. As a result, the recommended intensities sometimes show large variations (Table 6.7). By comparing the natural light intensities available inside the greenhouse (Table 5.3) with the desired light intensities for specific crops (Table 6.6) and light levels available at the final destination (the home of the consumer, Table 6.7), an assessment can be made of the best possible production methods. As much as possible, the recommended light sums required are shown in the various graphs presented in this section. Based on this data, an estimate can be made whether supplemental lighting is necessary, and if so, what light intensity is needed.



Yucca originates from subtropical Central America and has a high to very high light requirement.

Table 6.6. ***Recommended light intensities for growing of various foliage plants.***

This data originates from the US. The data in Columns 1 and 2 are often higher than the values used and attainable in The Netherlands. The data in Columns 3 (Florida) and 4 are more appropriate for the Dutch conditions. It is clear that plants can adjust to different light intensities. However, the question remains, which light intensity, is optimal for successful greenhouse production.

Column 1:
Original data in footcandles, converted to µmol m^{-2} *s*$^{-1}$ *using a conversion factor of 0.20 (Thimijan and Heins, 1983).*
1,000 ft-c = 200 µmol m^{-2} *s*$^{-1}$*(solar radiation)*
Source: Roy Larson, 1992.

Column 2:
These values have been derived and adjusted from: Conover, 1991; Conover and McConnell, 1981; Vladimirova et al., 1997.
1,000 fc = 200 µmol m^{-2} *s*$^{-1}$ *(solar radiation)*
Source: John Dole and Harold Wilkins, 1999.

Column 3:
Optimum values for Florida, based on research by Poole and Conover, 1996.
Source: Wolfgang Horn, 1996.

Column 4:
Based on empirical data.
Source: Lynn P. Griffith Jr., 1998.

	PPF µmol m^{-2} s^{-1} 1	PPF µmol m^{-2} s^{-1} 2	PPF µmol m^{-2} s^{-1} 3	PPF µmol m^{-2} s^{-1} 4
Adiantum spp.	-	-	-	240-360
Aglaonema commutatum	-	-	130-330	300-500
Aphelandra squarrosa	200-300	200-300	-	160-300
Asparagus spp.	-	-	330-600	500-900
Asplenium spp.	-	-	-	300-400
Begonia Rex hybrids	-	-	-	400-600
Calathea spp.	-	-	130-330	200-300
Chamaedorea	500-700	300-600	200-400	300-600
Chlorophytum	-	-	130-330	200-500
Chrysalidocarpus lutescens	-	-	530-800	700
Cissus rhombifolia	-	300-500	200-400	240-400
Codiaeum variegatum	1,400-1,600	600-1,600	530-800	500-640
Coffea arabica	-	-	130-330	-
Cordyline fruticosa	600-800	500-900	200-400	600-700
Dieffenbachia	500-800	300-600	200-400	300-600
Dizygotheca elegantissima	-	-	-	400-800
Dracaena deremensis	600-700	400-700	-	300-350
Dracaena fragrans	1,000-1,200	400-700	200-400	600-700
Dracaena marginata	1,000-1,200	600-800	330-600	600-1,200
Epipremnum pinnatum	600-800	300-800	200-400	300-700
Fatsia japonica	-	-	-	200-1,200
Ficus benjamina	1,000-1,200	600-1200	530-800	700-1,000
Ficus elastica	-	800-1,600	530-800	1,000
Ficus lyrata	-	1,000-1,200	530-800	800
Hedera helix	-	300-500	200-400	300-500
Howeia forsteriana	-	-	-	500-1,200
Maranta spp.	200-400	200-500	-	200-500
Monstera deliciosa	700-900	500-900	330-600	-
Nephrolepis exaltata	400-600	300-700	200-400	300-600
Peperomia spp.	500-700	300-700	200-400	200-600
Philodendron hybr.	500-600	300-1,000	200-400	200-400
Philodendron scandens	-	-	200-400	300-600
Philodendron selloum	-	-	530-800	600-1,200
Pilea spp.	500-600	300-600	-	200-400
Platycerium bifurcatum	-	-	-	240-360
Pteris spp.	-	-	-	240-360
Radermachera sinica	-	-	-	600-700
Sansevieria trifasciata	-	-	200-800	700-1,000
Schefflera arboricola	1,000-1,200	800-1,200	330-600	1,200
Syngonium podophyllum	600-800	300-700	200-400	300-700
Yucca elephantipes	-	700-900	330-600	600-1,000

Table 6.7. ***Minimum light levels for foliage plants grown under living room conditions.***

Column 1:
Required light intensity for durable interior plantings
10>50 indicates at least 10 but preferably more than 50 µmol m^{-2} *s*$^{-1}$
The original values were given in lux. The conversion into µmol m^{-2} *s*$^{-1}$ *was based on:*
1,000 lux = 18 µmol m^{-2} *s*$^{-1}$
Source: FFL Richtlinie Fassadenbegrünungen, 1995, Bonn.

Column 2:
Based on empirical data. The original values were presented in lux. The conversion into µmol m^{-2} *s*$^{-1}$*was based on):*
1,000 lux = 18 µmol m^{-2} *s*$^{-1}$
Source: Wolfgang Horn, 1996.

Column 3:
Based on empirical data.
15-30 > 50 indicates at least 15-30, but preferably more than 50 µmol m^{-2} *s*$^{-1}$ *to maintain color or some growth.*
Source: Lynn P. Griffith JR., 1998.

	PPF µmol m^{-2} s^{-1} 1	PPF µmol m^{-2} s^{-1} 2	PPF µmol m^{-2} s^{-1} 3
Aglaonema commutatum	20-50	10	20 >30-50
Asparagus spp.	20 >75	20	20 >30-50
Begonia Rex hybrids	50 >75	-	80
Calathea spp.	20 >75	-	30 >80
Chamaedorea elegans	20-75	10	15-30
Chlorophytum spp.	20-75	-	15-20 >30-40
Chrysalidocarpus lutescens	50 >75	-	30-80
Cissus rhombifolia	10 >75	10	15-20 >30-80
Codiaeum variegatum	50 >75	20	100-200
Cordyline terminalis	20 >75	-	15-30
Dieffenbachia maculata	10-50	15	30-50
Dizygotheca elegans	50 >75	20	60-200
Dracaena deremensis, fragrans	20 >75	-	10 >20-30
Dracaena marginata	20-75	15	15-20 >40
Epipremnum pinnatum	20-75	10	30-50
Fatsia japonica	10 >75	-	20 >30-50
Ferns	10-75	15	15-30 >50
Ficus benjamina	50 >75	20	30-50
Ficus elastica	10 >75	10	15-20 >40
Hedera spp.	10 >75	-	30-50
Maranta spp.	20-75	-	15-30
Philodendron scandens	10-50	10	10 >10
Radermachera sinica	50-75	-	50-60
Sansevieria trifasciata	20 >75	-	10-15
Schefflera arboricola	10-75	10	15-50
Syngonium podophyllum	10-75	-	15 >20-30
Yucca elephantipes	50 >75	10	30 >50
Zebrina spp.	20-75	-	15-50

6.2 Lighting Recommendations for Various Crops

6.2.5 Lighting of flowering pot plants

Introduction

Flowering pot plants can be divided into three groups based on their light requirements:

High to very high light: 20-50 mol m^{-2} d^{-1}:
Cyclamen, Dendranthema, Euphorbia pulcherrima, Gerbera, Hibiscus, Hydrangea, Kalanchoe, Pelargonium peltatum, zonale and grandiflorum hybrids, Rosa

Medium light : 10-20 mol m^{-2} d^{-1}:
Begonia elatior, Bromeliaceae, Exacum, Pelargonium peltatum hybrid, Sinningia, Streptocarpus

Low light: 5-10 mol m^{-2} d^{-1}:
Phalaenopsis, Saintpaulia, Spathiphyllum

Most flowering pot plants are grown in the Netherlands under suboptimal light conditions for the major part of the year. From the end of September to mid-March, the light sums in the greenhouse are on average less than 10 mol m^{-2} d^{-1}. For plants with a medium or high light requirement, this light sum is too low. Even African violets, which have a low light requirement experience a shortage of light during the winter months and may benefit considerably from supplemental lighting.

During summer, light sums inside the greenhouse are between 25 and 30 mol m^{-2} d^{-1}. While these light levels are sufficient, sometimes the light sum is much lower due to the use of shading.Shading prevents high temperatures and/or high light intensities in the greenhouse. During summer, the light intensity inside the greenhouse may be as high as 1,400 μmol m^{-2} s^{-1}, which is too high for all species of pot plants (Table 6.8). Shading is applied as early as February/ March, particularly for those crops that are not used to (sudden) high light intensities. Therefore, shading is needed, but the result is a reduced light sum. The light intensities which are use to recommend the use of shade curtains give an indication of how much light is required for good growth. The installed supplemental lighting installation should be able to provide up to these light levels.

Supplemental lighting can provide useful effects for most of the year, depending on the installed lighting installation (Table 6.7). Production timing and plant size can be improved by lighting during the winter. Research showed that the number of flowers in many pot plants increased using high light intensities.

Plants showing a strong response to supplemental lighting are: Kalanchoe, pot chrysanthemum, and begonia. For these crops, plant size can increase with more than 20%. This effect is slightly less for Cyclamen and African violets, which show a 10-15% increase. Spathiphyllum shows increased branching but not a shorter production period. The number of flowers increases strongly in Kalanchoe and African violets, while begonia and cyclamen show a less pronounced response.

Most of the following lighting recommendations are based on research published by the Research Station for Floriculture and Greenhouse Vegetables in Aalsmeer, The Netherlands. Light sums are important elements in these prescriptions. Other guidelines come from Norway, where growers, even more than in the Netherlands, depend on supplemental lighting during the dark winter months.

Table 6.7. ***Effect of installed lamp wattage on the production period and plant size of flowering pot plants based on research data collected from various greenhouse operations.*** ***SON-T 400 W bulbs were used.*** *Source: Oprel, 1989.*

	Installed wattage m^2/lamp	light intensity μmol m^{-2} s^{-1}	production time (wks) winter	production time (%) summer	increase in prod. winter (%)	plant size (%) winter	increase (%) in plant size winter
Begonia 'Rosalie'	14	38	14.9	71.2	17	57	27
Chrysant 'Surf'	16	33	11.0	72.8	18	60	25
Cyclamen 'Pastel Vollebregt'	11	48	25.3	73.5	0	80	10
Kalanchoe 'Singapur'	15	35	18.2	72.6	10	60	32
Saintpaulia (African violet)	14	38	14.4	64.2	7	80	15

Begonia Elatior hybrids, Begonia x hiemalis, Rieger begonias

Introduction

Begonia elatior is a quantitative SD plant, which means that flowering occurs also under LD conditions. SD conditions accelerate flower initiation, while the development of the flower buds was stimulated primarily under LD conditions of at least 14 hours (Horn, 1996). During the winter, SD conditions are applied during the first one or two weeks, while during the summer, three weeks of SD, followed by LD conditions. The response period is 7-9 weeks.

Temperature

The temperature also influences flower initiation. For flower initiation SD conditions are required at temperatures above 24ºC (Sandved, 1971). This is a qualitative response. While maintaining a temperature up to 18ºC, Begonia Elatior flower initiation also takes place under LD conditions. The critical daylength is 12.5 to 13 hours at 24°C, while it is 11 hours at lower temperatures. The higher the temperature during the production of stock plants, the more delay in flowering can be expected (Verberkt, 1997).

Cultivar differences

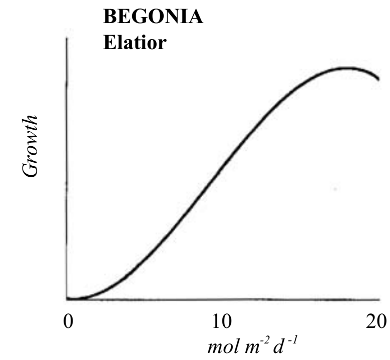
The current cultivars, however, respond very differently to SD. A longer period of short days resulted in, for the cultivar ‘Renaissance’, a faster and more uniform flowering, while the cultivar ‘Athen’ did not show any response (Verberkt, 1997). In addition to daylength and temperature, other factors also play a role in flowering such as plant age and light quantity.

Effect of light intensity

With increasing lighting intensity, the number of flowers increased while the response time became shorter (Mortensen, 1985). Increasing the light intensity from 45 to 130 µmol m^{-2} s^{-1} for the cultivar ‘Schwabenland’ reduced the response time to flowering from 79 to 68 days, while the number of flower buds increased from 36 to 54.

Daylength during production

Usually during production, when the shoots are 8-10 cm long, at least 2 weeks of SD conditions (9 hours) are maintained. For the cultivar ‘Netja’, after 24 days of SD conditions the flower buds had a diameter of approximately 1 cm (Verberkt, 1997). This cultivar is sensitive to SD conditions. For flower initiation, only a few days with SD conditions are required. The SD treatment can take place during transportation (e.g. while stored in a shipping area or inside the truck). For this cultivar, 4 to 5 days of SD conditions are enough for the development of a sufficient number of generative shoots. The longer the SD period, the fewer vegetative shoots and thus laterals with eventually flowers develop. The plants remain short with less fresh mass, not only ‘Netja’ but many other cultivars as well. The cultivars ‘Barkos’, ‘Renaissance’, ‘Pinto’, and ‘Ann’ responded to the length of the SD treatment. Particularly during the winter, the length of the SD treatment comes at the expense of the daily light sum. Growth, shoot, and flower formation were delayed as a result (Verberkt, 1997).



The Begonia Elatior group consists of quantitative SD and DN cultivars. The critical daylength is about 13 hours. After potting, the plants receive about three weeks of LD treatment, followed by two weeks of SD treatment with a maximum daylength of 10 hours, and finally about five weeks of LD treatment with a daylength of at least 14 hours.
The crop has an average light requirement.

Other cultivars such as ‘Athen’, do not respond to SD, but these cultivars have many problems with malformed flowers and premature flowering during production so that flowers have to be pinched. SD-sensitive cultivars can be managed better. In addition to promoting the flower initiation, SD treatments also accelerate production, especially when approaching the longest day of the year. Before and after the SD period, a LD treatment is desired to stimulate both the vegetative and the generative growth of flower shoots.

Supplemental lighting

During the LD treatment, the use of supplemental lighting is very appropriate, but its use is limited during the SD treatment. Double cultivars of Elatior Begonia cannot be grown during the winter without supplemental lighting. The single cultivars benefit from supplemental lighting due to the increased number of shoots and better plant shape.

Lighting strategies

Experiments with lighting strategies indicated that supplemental lighting to daily photoperiod of 20 hours provided better results than by using the accumulated day or week sum. Using this strategy, the number of hours of effective lighting was higher (Verberkt, 1995b). The general rule is that the higher the light sums (intensity multiplied by duration) the more compact the plants become, with more sideshoots. Therefore, the use of growth regulators should be adjusted. Controlling plant growth and lighting strategy were closely related to the cultivar (Verberkt, 1990/1995b). Even when lighting is done as night break (*e.g.* from 22:00-04:00 hour), instead of daylength extension, the plants remain very compact. This has been observed for the cultivars ‘Aphrodite Radiant’ and ‘Laressa’ (Hendriks, 1988). A reduction in the production time of 2 or 3 weeks is possible but depends on cultivar, temperature, lighting period, and season. The cultivar ‘Schwabenland’ does not benefit from extended lighting, while the cultivar 'Rosalie' does (Table 6.7).

Effect of photoperiod

The lighting period affects shoot formation and consequently plant size. Usually the number of shoots is greatest using a 22-hour photoperiod. Increasing the photoperiod does not affect the number of leaves per shoot for this plant. The flower color is also influenced by the photoperiod. The cultivar 'Schwabenland' has the best red color under a 16-hour photoperiod, for the cultivar 'Rosalie' this is 20-22 hours. Longer photoperiods make the color more intense. During the middle of the winter, a 22-hour photoperiod for the cultivar 'Rosalie' leads to the greatest number of flower buds and flowers. When potting towards the end of January, a photoperiod of 22 hours was too long and 20 hours was preferred (Verberkt, 1990). Long photoperiods are not always beneficial for the keeping quality. For the cultivars 'Renaissance' and 'Rosanna' a 15-18 hour photoperiod is better than 21 hours. In conclusion, the optimal photoperiod is cultivar dependent and should be chosen carefully for each cultivar. These results are based on experiments in which the lamps were switched off as soon as the outside global radiation reached a value of 50 W m^{-2}. Lighting was therefore supplemental to the natural daylight. The actual duration of the supplemental lighting was shorter than the total length of the photoperiod.

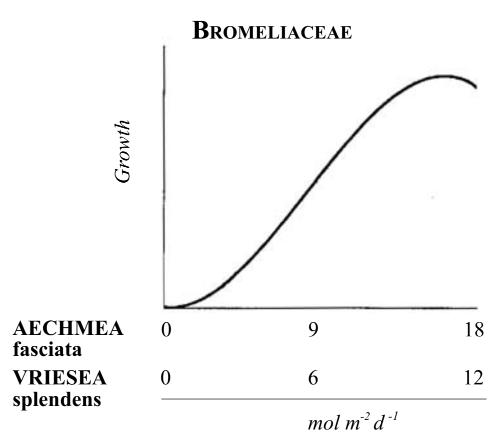
Required light sum and intensity

Usually growers supplement with a light intensity of 30 µmol m^{-2} s^{-1}. With continuous lighting for 20 hours, this results in an extra light sum of 2.2 mol m^{-2} d^{-1}, which doubles the natural light sum in a greenhouse in December in the Netherlands. For begonia, the installed supplemental lighting intensity is relatively low (Table 6.7). Begonias can endure a reasonable light intensity. In spring, shading is usually started at about 325 W m^{-2} of outside global radiation (DLV, 1994). This corresponds with a light intensity inside the greenhouse of about 400 µmol m^{-2} s^{-1}. After mid-March, this light intensity may occur during the middle of the day. In the Netherlands, the average daily light sum in March is about 10 mol m^{-2} d^{-1}. Insufficient shading can result in a delay of growth and a less intense red leaf color. These effects can also be the result of excessive lighting. For some cultivars, the leaf serrations become deeper. Too much shading during summer results in long, and weak plants with many leaves. During the summer, the target light levels for shading can be increased. In Norway, the cultivar 'Barkos' was lit with 47 to 188 µmol m^{-2} s^{-1} for 20 hours starting in late January, after a SD treatment of five weeks. Flowering was accelerated and dry mass increased (Gartner Yrket, 1998) as light sums increased from 3.4 to 13.6 mol m^{-2} d^{-1}. Furthermore, it was observed that lighting every day is better than, for example, lighting on alternate days with double the intensity. Other experiments showed that net photosynthesis was doubled when the light intensity was increased to 105 µmol m^{-2} s^{-1} while maintaining a CO_2 concentration of 1,500 ppm. The greatest increase, however, was obtained while using a light intensity up to 35 µmol m^{-2} s^{-1}, after which the positive effects started to diminish (saturation effect). The same was true for CO_2 concentrations exceeding 900 ppm (Mortensen, 1985). The data presented here indicate that the supplemental light intensity of 30 µmol m^{-2} s^{-1}, which is commonly used in the Netherlands, is too low from a plant physiology perspective. A supplemental lighting intensity of 35 µmol m^{-2} s^{-1} appears to be a more appropriate minimum.

Bromeliaceae

The species belonging to this group are indigenous to South-America. With the exception of pineapple, they grow in tropical rainforests on trees (epiphytically) around the equator (particularly Brazil) at a daylength of about 12 hours. Pineapple and several Aechmeas, originate from the high mountains where they normally grow in soil. The various species show differences in light response. Shading is done mostly to prevent radiation damage from direct sunlight. Shading is first applied only in the direction of the sun. This is possible in wide-span greenhouses (with an E-W orientation) with screens installed along the roof segments. When the sun angle increases, both sides of the roof have to be shaded. Shading is usually started at an outdoor global radiation of about 300 W m^{-2}, which corresponds with an inside light intensity of 375 µmol m^{-2} s^{-1} (DLV, 1994).

Research showed large differences in sensitivity (inside light intensities) : Guzmania and Vriesea 250 µmol m^{-2} s^{-1}, Nidularium 350 µmol m^{-2} s^{-1}, Aechmea 450 µmol m^{-2} s^{-1}, Cryptanthus and Tillandsia lindenii (LD plant) 500 µmol m^{-2} s^{-1} (Horn, 1996).



The family of Bromeliaceae consists of SD, LD, and DN species. As yet, limited information is available. Probably high temperatures promote flowering.

It is known, however, that the pineapple is a quantitative SD plant. Shorter daylengths and lower temperatures promote the flower initiation.

Vriesea and Aechmea have an average light requirement.

Bromelias need light for germination, and seeds should therefore not be covered. Lighting is standard practice after seeding and during the seedling stage. This reduced the production time till potting, which can be very long. Commercially, supplemental lighting is provided at 50 µmol m^{-2} s^{-1} and a photoperiod of approximately 16 hours (Horn, 1996). This also results in a shorter production time during the winter. Supplemental lighting can improve plant quality, particularly in Vrieseas. During the winter, the inflorescence becomes less branched than during the summer, which is an important quality characteristic. Lighting during production with 50 µmol m^{-2} s^{-1} appears to be a minimum requirement. In a 2-layer production system, excellent results can be obtained with supplemental lighting. However, the production period after re-spacing was shown to be uneconomical in this production system.

Calceolaria hybrids

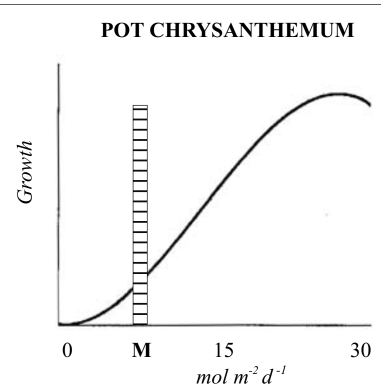
This is a quantitative LD plant. After flower buds are initiated (4-6 weeks at 8°C), a photoperiod of 16-18 hours is optimal for flower bud development. The period until flowering is shortened with an extended photoperiod. During the winter, daylength extension is often conducted with fluorescent lamps (4.6 µmol m^{-2} s^{-1}). The light spectrum of these lamps prevent excessive stretching compared to incandescent lamps (12 W m^{-2} installed capacity) due to the lack of far-red light. Generally, the greenhouse temperature is maintained at approximately 13°C. Plant temperature is increased when high-pressure sodium lamps are used (with 30-40 µmol m^{-2} s^{-1}), and, thus, air temperature can be lowered.

Pot chrysanthemum

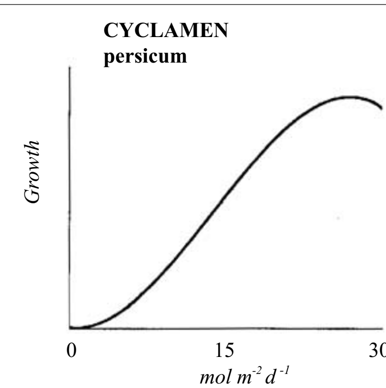
It is impossible to grow good quality pot chrysanthemums without supplemental lighting. With supplemental lighting, the year-round supply, the utilization of the greenhouse space, and the labor requirements are optimized. Lighting during the winter months with approximately 150 µmol m^{-2} s^{-1} is customary. For further details, see the section on Chrysanthemum, cut flowers and stock plants.

Cyclamen persicum

Cyclamen has a high light requirement. Under high light conditions plants become sturdier and flower sooner compared to under low-light conditions. Although Cyclamen is DN, daylength and intensity influence the rate of flower initiation and development. However, Cyclamen cannot endure prolonged periods with a high (sun) light intensity. Shading is applied as soon as the outside global radiation reaches 275 to 600 W m^{-2} after mid-March, depending on the developmental stage (this corresponds with an inside intensity of 350-750 µmol m^{-2} s^{-1}). Shading is used to control the temperature as well. Experiments with shading values between 200 and 800 W m^{-2} (or 250-1,000 µmol m^{-2} s^{-1} inside the greenhouse) indicated that the number of leaves increased while leaf size decreased under increased light levels (Arendts, 1989). The plants remained more compact when shading was applied at outdoor global radiation levels above 600 W m^{-2} (Verberkt, 1997). Leaf necrosis (sun scald) occurred at an inside light intensity above 800 µmol m^{-2} s^{-1} (Verberkt, 1997; Dole, 1999), but when the leaf temperature remains below 25°C, cyclamen could endure higher light levels (Karlsson, 1997). The vegetative growth stopped below 1 mol m^{-2} d^{-1} while the generative growth still continued (Rünger, 1986). Table 6.7 shows that lighting during the production period had little effect at a light intensity of 48 µmol m^{-2} s^{-1}. Timing was not affected but it has been demonstrated that a high light intensity for longer periods of time accelerated flower development (Neuray, 1973). Perhaps the lighting strategy was not optimal (intensity and duration). German experiments have confirmed a shorter cropping cycle is possible using supplemental lighting. However, the strong increase of leaf petiole and flower stem length resulted in weaker plants (Bettin, 1988). For seed production, lighting is considered profitable using a light intensity of 32-35 µmol m^{-2} s^{-1} for the production of open-pollinated culti-



*Chrysanthemum is a quantitative SD plant. The critical daylength is between 10 and 12 hours. For the vegetative growth 16 hours or more is needed. The minimum light sums (**M**) for easy flower initiation and vegetative growth are between 4.6 and 6.8 mol m^{-2} d^{-1}. The crop has a high light requirement.*



Cyclamen is a DN plant. The flower initiation rate and development were stimulated by the light sum (Neuray, 1973). During winter, more leaves are initiated before the initiation of the first flower than during summer.
Cyclamen has a high light requirement.

vars. Thus, 10 hours of supplemental lighting, resulted in a light sum of 1.2 mol m^{-2} d^{-1}, which improved pollination. Lighting also prevented stems from rotting (decay) when pollination was not successful.

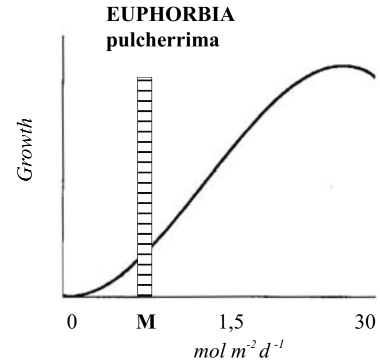
Euphorbia pulcherrima (poinsettia)

For the normal single-stem and pinched crop (potting mid August/beginning of September), the initiation and subsequent development of flowers and bracts take place during a period of natural SD towards the end of September (15-25). During this period of the year and in The Netherlands, the light sum drops below approximately 6.6 mol m^{-2} d^{-1} which is the required limit for optimal branching (Ludolph, 1994). No supplemental lighting is needed, since sprouting of the axillary buds of the pinched crop takes place in the period prior to that. Still, supplemental lighting during the SD period is useful, especially for late crops such as the mini-poinsettias.

Favorable effects of supplemental lighting are: a more uniform shoot development, improved flower bud formation (cyathia) and development of bracts, improved quality due to a more intensive color of the bracts and keeping quality of the cyathia ('berries'), heavier plants which can withstand shipping and fungal diseases (*e.g. Botrytis*), fewer culls, and assurance of quality during low-light years. For mini-poinsettias, the benefits are: shorter production period, expansion of bracts, and more plants per square meter.

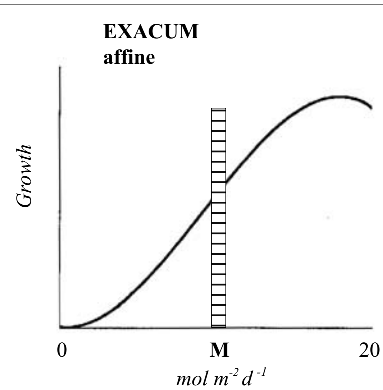
Supplemental lighting is provided with an intensity of 35 µmol m^{-2} s^{-1} for 10 hours during daytime (because of SD) or 1.3 mol m^{-2} d^{-1}. This light intensity is a target value since research has demonstrated that an increase from 12 to 73 µmol m^{-2} s^{-1} has positive effects (Moe, 1992).

For the development of bracts, a minimum target light sum of 4.6 to 5.3 mol m^{-2} d^{-1} was recommended (Ludolph, 1994). If the light sum is lower than 4 mol m^{-2} d^{-1}, the plant diameter declines. Table 5.3 shows that the average light sum inside the greenhouse in November, in The Netherlands, is 3.6 mol m^{-2} d^{-1} and in December 2.3 mol m^{-2} d^{-1}. It is clear that supplemental lighting is needed to reach the target light sum. For comparison, in Norway, supplemental lighting is provided throughout the entire production cycle: during the LD phase an intensity of 75 µmol m^{-2} s^{-1} with a 18-24 hour photoperiod and CO_2 enrichment are provided, and during the SD phase an intensity of 40-75 µmol m^{-2} s^{-1} with a 10-hour photoperiod is provided. This results in additional light sums of 6.5 and 2.7 mol m^{-2} d^{-1}, respectively (Ludolph, 1994). During the SD phase the total light sum in Germany is almost equivalent to that in The Netherlands.



*Poinsettias are quantitative SD plants. The critical photoperiod is 12.5-13 hours. The minimum light sum for optimal branching is 6.6 mol m^{-2} d^{-1} (**M**) Pot plants have a high light requirement, depending on the cultivar; stock plants with larger leaf areas have a very high light requirement.*

Since the poinsettia is photoperiod sensitive, stray light (with an intensity as low as 2 lux) during the SD period should be avoided. Supplemental lighting provided in adjacent greenhouses can delay flower induction and bract expansion. Once inside the living room, sufficient light should be available for a good keeping quality. To prevent dropping of leaves and berries, a light level of at least 7 -10 µmol m^{-2} s^{-1} or approximately 600-850 lux is required (Lange, 1984). The latter intensity is near the light compensation point when as many carbohydrates are produced as respired (no net growth).



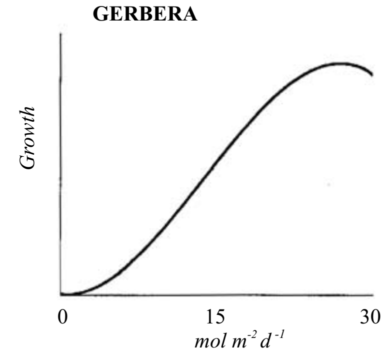
Exacum is a DN plant with an average light requirement.
*For good quality, a minimum light sum of 10.5 mol m^{-2} d^{-1} (**M**) is necessary.*

Exacum affine

This annual originates from the island of Socotra, is propagated by seed and cuttings. Light is required for seed germination. Exacum is not photoperiod sensitive. The flower development is stimulated by high light sums, and therefore the main production period is from May to September. Lighting results in compacter plants, which need little growth regulation. Other positive effects are: improved branching and flower advancement, because flowering depends on the light sum. In the US, high quality plants have been obtained by cultivation under fluorescent lamps at an intensity of 183 µmol m^{-2} s^{-1} and a 16-hour photoperiod (Holcomb, 1983). The method of lighting should be adjusted to the season. It is recommended to apply supplemental lighting to maintain a 18-hour with a light intensity of 50 µmol m^{-2} s^{-1}, resulting in an additional light sum of 3.2 mol m^{-2} d^{-1} (Anon., 1992). Based on Holcomb's research, a higher light intensity during the winter would be preferred.

Gerbera hybrids

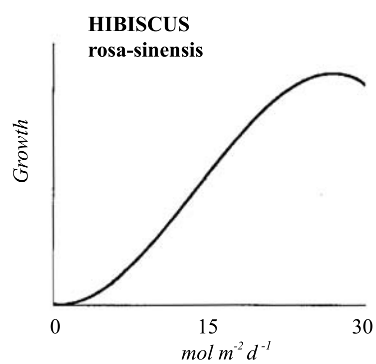
These plants have a high light requirement. During the winter months, the production period increases considerably, while the flower bud development and the keeping quality strongly decline. An accumulation of flower buds develops, which abort under low light conditions. Flower initiation and development were dependent primarily on light sum and temperature (Erwin, 1991). SD had very little impact (Rogers, 1990), but accelerated the development of flowers, stimulated the branching of rhizomes and, consequently, the number of flower buds (Leffring, 1981). A large amount of light is required during seedling production. Supplemental lighting with an intensity of 100 μmol m^{-2} s^{-1} significantly improved germination of the light-requiring seed, dry mass of seedlings, and shortened the production period till first flowering (Erwin, 1991). Lighting during the winter (mid-December to the end of March) with an intensity of 60-70 μmol m^{-2} s^{-1} and a maximum photoperiod of 20 hours resulted in a quadrupling of the number of flower buds (Ludolph, 1993), while the production period was reduced by 20-30%. A number of quality characteristics such as number of sideshoots and flower size were improved. During these experiments, supplemental lighting has provided at a light sum of 120 klxh d^{-1} or approximately 8 mol m^{-2} d^{-1}.



Gerbera is a quantitative SD plant. Flower initiation and development depend mainly on light sum and temperature. Air temperatures of 20°C or higher inhibit flower development. Gerbera as pot plant has a high light requirement.

Hibiscus rosa-sinensis

This DN plant is indigenous to subtropical and tropical countries, and requires high light conditions. Flower bud initiation was primarily determined by the light sum (Wilkins, 1986). Optimum light intensities for this crop vary from 400 to 1,300 μmol m^{-2} s^{-1} (Dole, 1999). Shading is provided only to prevent extreme high temperatures. Lighting during the winter months stimulated shoot development and the number of flowers, and reduced the production period while shoot length became shorter with an increasing light sum (Ludolph, 1990). Extending the photoperiod did not increase the number of leaves per shoot. Plants receiving only natural light were of lower quality. An increase in the light sum from approximately 2 to 7.5 mol m^{-2} d^{-1} (from December to the beginning of March) resulted in a doubling of the number of flowers, an 30% increase in the number of shoots, and a reduction in the production period by 12%.

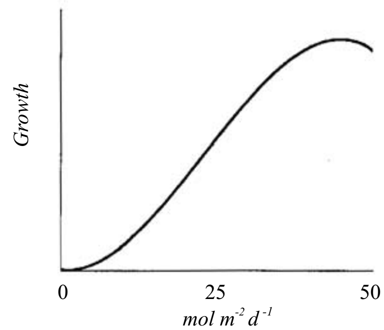


Hibiscus is DN.
Flower initiation is mainly affected by the light sum. The plant has a high light requirement.

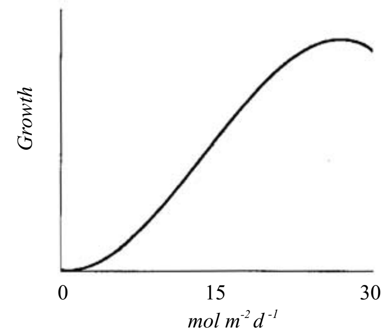
At the research station in Hannover, Germany, supplemental lighting was provided with an intensity of 60-70 μmol m^{-2} s^{-1} and a 20-hour photoperiod to reach a total light sum of about 7.5 mol m^{-2} d^{-1}. To avoid irregular flower bud development, minimum light sums of 4-5.5 mol m^{-2} d^{-1} were needed, but higher levels are preferred (Ludolph, 1993). Hibiscus is sensitive to flower bud abortion. Small flower buds drop more easily than bigger buds under low light conditions. During shipping, this becomes quite evident. When plants are transported in the dark, those grown under high light conditions suffer less from bud abortion than those grown under low light. Bud abortion during the flowering stage could be reduced by providing supplemental lighting with sufficient red light (4 μmol m^{-2} s^{-1}) using red light emitting diodes (LED) (Van Lieburg, 1989). Hibiscus is very sensitive to ethylene (*e.g.* present in boiler combustion gases), resulting in bud abortion.

Hydrangea macrophylla

Hydrangeas have a very high light requirement. Light intensities of less than 400 μmol m^{-2} s^{-1} delayed flower initiation and the development of inflorescences after the cold treatment (Litlere, 1975). The incidence of blind shoots was caused mainly by low light levels (Horn, 1996). For optimal vegetative growth, which normally takes place outdoors, a light intensity of 1,000-1,500 μmol m^{-2} s^{-1} was necessary (Dole, 1999). Flower initiation took place under moderate night temperatures of 13-18°C during late summer. Between 19-21°C, a LD treatment (14 hours or more) could delay flower initiation, while a SD treatment accelerated it (Peters, 1975). Higher temperatures further delayed flower initiation. SD caused dormancy. Sup-



Hydrangea is a DN plant at temperatures between 13 and 18°C, but outside this range, the plant does respond to long and short days. Flower initiation and dormancy are the result of SD treatments with temperatures below 18°C.
Hydrangea has a very high light requirement.



This pot plant is a SD plant.
The critical daylength is 11.5 hours.
Kalanchoe has an average light requirement.

plemental lighting can be used for forcing of hydrangeas.

The stem length was increased with supplemental lighting through an increase in either light intensity and/or photoperiod. Therefore, additional chemical height control or negative DIF should be applied (Verberkt, 1995a). For early forcing, (weeks 44-03) supplemental lighting with an intensity of 45 μmol m^{-2} s^{-1} and a 20-hour photoperiod resulted in a distinctly shorter forcing period compared to the use of a light intensity of 15 μmol m^{-2} s^{-1} and a 16-hour photoperiod. When forcing started in week 8, no benefits were observed (Verberkt, 1995a). Positive effects of lighting during the winter using a 20-hour photoperiod and a light intensity of 30 μmol m^{-2} s^{-1} include a reduction of the forcing period during the middle of the winter by 7-10 days as well as a better inflorescence development (Verberkt, 1995b). During these experiments at the Research Station for Floriculture and Glasshouse Vegetables, The Netherlands, no difference was shown between lighting with a maximum target light sum of 3 mol m^{-2} d^{-1} (during week 51) and lighting with a an intensity of 30 μmol m^{-2} s^{-1} and a 20-hour photoperiod.

At the Research Station in Wolbeck, Germany, it was shown that lighting could reduce the forcing period by 22%. Furthermore, sprouting of the axillary buds was more reliable, which resulted in an improved plant shape. Due to the increase in plant height, it is generally recommended to provide lighting for no more than 30 days. Later experiments with the cultivars ‘Libelle’ and ‘Leuchtfeuer’, showed that lighting for a three-week period resulted in 5 cm shorter plants. Plant height for these cultivars was the same when supplemental lighting was provided for 6, 8 or 12 weeks at an intensity of 40 μmol m^{-2} s^{-1} and a 16-hour photoperiod. The light requirement of white cultivars appeared to be lower compared to the red flowering cultivars (Strauch, 1990). The optimum duration of the photoperiod depends on cultivar and growing season. Occasionally, growers provide supplemental lighting only during the first 4 to 5 weeks of forcing (of a total of 7-10 weeks) with a 4-5 hour dark period. Usually a PPF of 30 μmol m^{-2} s^{-1} is used.

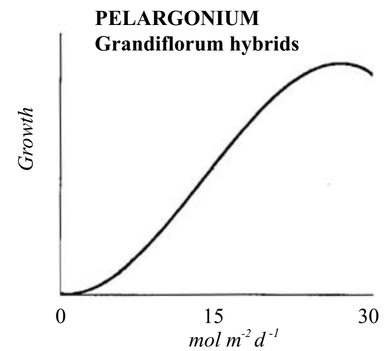
Kalanchoe blossfeldiana

As few as two days of a SD treatment were sufficient for flower initiation. The number of flowers increased proportionally to the increase in the number of days of the SD treatment. Depending on the cultivar, 2 to 3 weeks were necessary to complete the development (Nell, 1982). Commercial growers frequently provide SD conditions through the end of the growing period, because LD conditions during the SD treatment results in a delay of flowering. A minimum of 40 days of SD treatment was recommended for many cultivars (Dole, 1999).

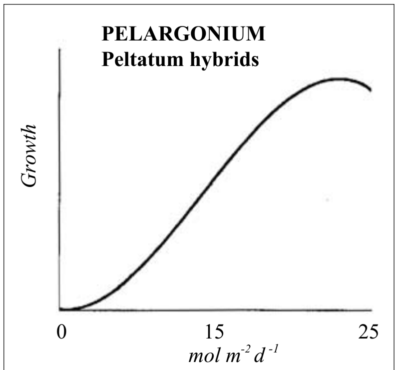
Table 6.7 shows a significant impact of supplemental lighting of plant size. The effects on response time are less evident. The response to lighting depends on cultivar, season, and (total) light sum.

In The Netherlands, supplemental lighting is usually provided during the production phase. Partly, this is due to competition from Denmark where supplemental lighting is used for a longer period. As a result of this extra light, more first quality plants develop with more flower buds and increased branching. The light sum has a large impact on the number of flower trusses. For Kalanchoe, as well as for Hedera helix, Elatior begonia, and seed geranium, both light intensity and light sum are important. For example, a light intensity of 68 μmol m^{-2} s^{-1} and a 20-hour photoperiod gives better results compared to and intensity of 85 μmol m^{-2} s^{-1} and a 16-hour photoperiod, or a light intensity of 57 μmol m^{-2} s^{-1} and a 24-hour photoperiod (these conditions result in equal light sums of 4.9 mol m^{-2} d^{-1}). A particular combination of light intensity and photoperiod appears to be optimal for a given production phase. In Norway, a light sum during the winter of 12 mol m^{-2} d^{-1} is optimal for the cultivar ‘Debby’ (using a light intensity of 140 μmol m^{-2} s^{-1} and a 20-hour photoperiod; Gartner Yrket, 1998).

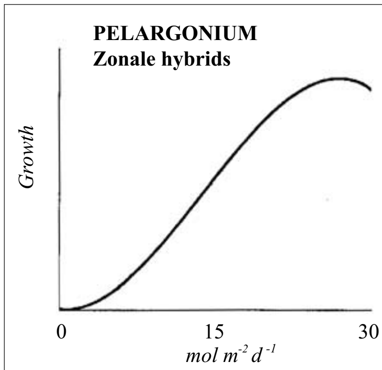
As a SD plant, Kalanchoe is grown using a 10-hour photoperiod for 5-6 weeks using black-out cloth. After this period, the photoperiod could be increased to improve the development of the inflorescence (Verberkt, 1990b). A 22-hour photoperiod after the SD treatment instead of 16 hours shortened the production



Regal pelargonium is DN. Flowering is stimulated by LD treatments and high light sums. Many cultivars need a cold period for flower initiation. The light requirement is high.



Ivy geraniums are DN. They have an average to high light requirement.



Cutting and seed geranium are DN and have a high light requirement.

time by several days when grown from November to January. Overall, supplemental lighting can shorten the production time by 7-10 days, using HPS-lamps and an intensity of 30 µmol m^{-2} s^{-1}, during flower initiation and flower development.

The fresh and dry mass of plants and flowers, as well as the number of side shoots increased during the winter months, proportional to the length of the photoperiod. The flower stem length also increases, which could result in the use of more chemical height control. Beyond the period November/January, the photoperiod can be reduced to 18 hours. The lamps are switched on as soon as the outside global radiation drops below 50 W m^{-2}. During the winter, lighting could result in different flower colors (*e.g.* the normally yellow cultivar 'FortyNiner' becomes yellow/orange).

Ultraviolet light

German experiments (Hoffmann, 1999) have shown that UV-A radiation intensifies anthocyanin formation in flowers of the cultivar 'Colorado'. UV-B radiation had the same effect. Also in the leaves, more anthocyanins were formed. Using special lamps or special glazing can test this. Excessive anthocyanin formation occurred when the light intensity in the greenhouse exceeded 1,160 µmol m^{-2} s^{-1} (Schwabe, 1985). Above this level, shading should be applied, partly to prevent high temperatures. At temperatures above 27°C, flowering was delayed (Schwabe, 1985). The day and night rhythm of flower closure was also affected. The earlier in the night the supplemental lighting is started, the sooner the flowers close during the day (Verberkt, 1990b).

Supplemental lighting and carbon dioxide

In Norway, various combinations of carbon dioxide concentrations and light intensities have been tested. The best combination appeared to be a CO_2 concentration of 800 ppm and a light intensity of 94 µmol m^{-2} s^{-1} during a 20-hour photoperiod (fresh mass increased by 54% compared to 365 ppm CO_2). A light intensity of 56 µmol m^{-2} s^{-1} combined with a CO_2 concentration of 800 ppm increased fresh weight by 27%. The same results were obtained with a light intensity of 94 µmol m^{-2} s^{-1} and a CO_2 concentration of 365 ppm. Carbon dioxide enrichment can partly compensate for lower light levels.

Pelargonium hybrids (geranium)

Pelargonium zonale (zonal geranium), peltatum (ivy geranium) and grandiflorum hybrids (Martha Washingtons, also known as regal pelargonium) are DN plants. Initiation and development of the flowers very strongly depended on light sum and the corresponding temperatures (Langton, 1985). These plants can be successfully grown based on light sums.

Regal pelargonium

Flowering of the regal pelargonium could be accelerated by applying LD conditions after a cold treatment of about 5-6 weeks at daily average temperatures between 2 and 7°C (Hackett, 1974). Increasing the night temperatures from 2 to 6°C increased the total number of florets (Erwin, 1992). With the exception of several newer cultivars, these plants need low temperatures for flower bud initiation, while LD conditions and high light sums stimulate the flower development. The cold treatment could be given in cool production areas at a light intensity of 390 µmol m^{-2} s^{-1} for 3-6 weeks (Erwin, 1992). LD conditions could be applied when the initiation of the flower parts is completed (Nilsen, 1975). The natural daylength is then extended to a 16-18 hour photoperiod and a light intensity of 130 µmol m^{-2} s^{-1}, according to American research (Fonteno,1992). This can only be achieved with high-pressure sodium or fluorescent lamps. In The Netherlands during the winter, a light intensity of 35 µmol m^{-2} s^{-1} is regarded as sufficient. Under ambient high light levels (650 µmol m^{-2} s^{-1}), day length extension with incandescent lamps suffices (Fonteno, 1992). UV-A increases the anthocyanin content of the flowers, UV-B stimulates this further. Consequently, for a more intense color of the flowers, a lamp type that emits UV-radiation as well is recommended.

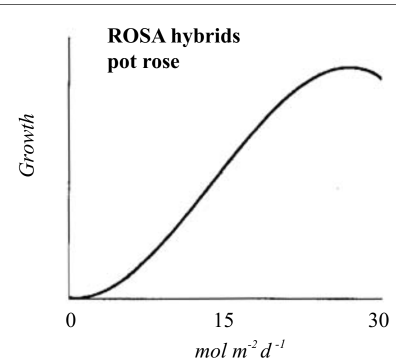
Seed geranium

The seed geranium has three different developmental stages (Wetzstein, 1983). The first stage is from germination to when the flower buds are visible with a microscope, the second stage from the microscopic size to when the flower buds are visible with the naked eye, and the third stage from visible flower buds to the opening of the first floret of the inflorescence. The duration of these stages is mainly based on the rate at which the plantlets are able to develop the first 6-8 leaflets. During the first two stages, the light sum plays an important role, while in the third stage the temperature is the crucial factor. From 10 to 25°C the length of the third growth stage declines almost linearly from 80 to 20 days. At 15°C the biggest flowers were obtained, and the flowers became smaller when temperatures deviated from this value (Armitage, 1981).

Increasing light intensities, or light sums during the first 4 weeks after germination advanced the flower initiation. Seedlings of 4-5 weeks old were even more sensitive to supplemental lighting than 1-3 week old plantlets (Kaczperski, 1995). At that stage, the well-known rule of thumb applies that 1% more light is 1% more growth (Aimone, 1985). The light intensity should be at least 70 μmol m^{-2} s^{-1} for 16 hours (Armitage, 1981; Bethke, 1985). Increasing the light intensity from 50 to 100 μmol m^{-2} s^{-1} reduced the first two stages from 87 to 67 days, at 21-23°C (Armitage, 1981). Using a 18-hour photoperiod, the light sum increased from 3.2 to 6.5 mol m^{-2} d^{-1}. Below 3 mol m^{-2} d^{-1}, growth develops too slowly, because the PPF of 50 μmol m^{-2} s^{-1} is close to the light compensation point at 21°C. At 20°C, the light compensation point is 46 μmol m^{-2} s^{-1}, and at 15°C it is 38 μmol m^{-2} s^{-1} (Armitage, 1981). In the range of 40-190 μmol m^{-2} s^{-1} development is slow, the optimum is generally around 450 μmol m^{-2} s^{-1}, and above 900 μmol m^{-2} s^{-1} shading is needed (Fischer, 1994/1995).

Under higher light intensities or light sums, plant height and leaf size declined, while branching and dry weight increase (White, 1984). The optimal light sum was reported as 21 mol m^{-2} d^{-1} (Erwin, 1993; White, 1984). This is far above the average light sums in the greenhouse in December and January (2.3 and 3 mol m^{-2} d^{-1}, respectively in The Netherlands). Consequently, lighting over long periods and with high intensities is necessary.

The leaf photosynthesis of plants raised under winter conditions is saturated at 700-1,100 μmol m^{-2} s^{-1}, depending on the temperature (15-31°C) (Armitage, 1981). This indicates that the geranium has a very high light requirement. Therefore, up to light intensities of 900 μmol m^{-2} s^{-1}, shading is not necessary, provided the temperature does not exceed 30°C.



Rose is DN.
Flowering is stimulated by high light sums.
The light requirement is high.

Peltatum and Zonale

Ivy geraniums have a lower light requirement with the maximum light levels depending on the cultivar. These varied from 400 μmol m^{-2} s^{-1} for the cultivar 'Amethyst' to 600 μmol m^{-2} s^{-1} for the 'Balcon' cultivars (Fonteno, 1992; Aimone, 1985). Zonal hybrids can best be grown at light intensities of 700-1,000 μmol m^{-2} s^{-1} (Dole, 1999). For early flowering, lighting with an intensity of 70 μmol m^{-2} s^{-1} and a 16-hour photoperiod is necessary.

Phalaenopsis spp.

This orchid needs high light levels during its dormant period, but during the growth period heavy shading is applied (Brieger, 1985). It is probably a SD plant with a very low critical daylength (Horn, 1996). The light intensity during the propagation phase is gradually allowed to increase from 40 to 160 μmol m^{-2} s^{-1}. Flowering plants can endure light levels up to about 300 μmol m^{-2} s^{-1} (Brieger, 1985).

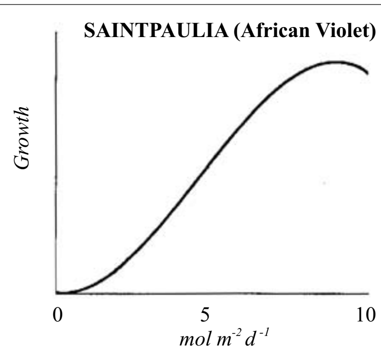
Although this orchid has a low light requirement, supplemental lighting shortens the time to harvest, reduces bud abortion, and increases flower diameter with 10-20%. In addition, bud abortion is reduced when grown at lower temperatures, such as 19/17°C. Experiments were conducted using a light intensity of 60 μmol m^{-2} s^{-1} for 10 hours from 06:00 to 16:00 hr (van Os, 1991). Recent experiments at the Research Station for Floriculture and Greenhouse Vegetables in The Netherlands, determined the effect of lighting on shoot production (Uitermark, 1996). For flowering at Mother's Day (middle of May), plants received a cool treatment of six weeks at 18°C, from mid-December to the end of January. Through 'cold' (vernalisation) and high-light conditions, the flowering stems were induced. Without supplemental lighting in April, a 60% rate of flowering was obtained, probably due to a low growth rate, and reduced rate of differentiation of leaves and flowers. As a result of additional lighting with an intensity of 38 μmol m^{-2} s^{-1} from 07:00 to 17:00 hr, more shoots developed. Supplemental lighting was provided during the daytime due to the SD sensitivity. The profitability of adding supplemental lighting can be increased by starting with plants that have initiated as few buds as possible at the beginning of the cool treatment. The plants have to be in a certain developmental stage in which flower initiation is possible. However, further research is needed. Phalaenopsis is a CAM plant that takes up carbon dioxide at night.

Rosa hybrids - pot rose

For good growth and flowering of pot roses, high light levels are necessary. The light compensation point of whole plants is about 70 μmol m^{-2} s^{-1} (Zieslin, 1990a). Sufficient growth can be obtained with higher light intensities only. During winter therefore, supplemental lighting will have to be provided at light intensities of *e.g.* 100 μmol $m^{-2} s^{-1}$ during 12 hours or longer (Dole, 1999). For fast root initiation of cuttings during the winter, a constant level of 134 μmol $m^{-2} s^{-1}$ during 24 hours is needed (Jorgensen, 1992). Higher light intensities are applied for production in northern countries. Norwegian research with 'Golden Hit' indicated an optimum light sum of 12 mol $m^{-2} d^{-1}$. To obtain this during winter in Norway, 140 μmol $m^{-2} s^{-1}$ was needed for 24 hours, in The Netherlands slightly less. Under such conditions, the largest number of flower buds developed which did not abort while the plants were kept in the living room. At the same light intensity, for the cultivars 'Honney' and 'Roxy' a light sum of 10 mol $m^{-2} d^{-1}$ is optimal considering the number of flowers and the forcing time. The photoperiod was 20 hours (Gartner Yrket, 7/1998).

Carbon dioxide enrichment can further increase the benefits of supplemental lighting, as Norwegian research has shown. The cultivars 'Sunset Parade' and 'Golden Hit' were grown under various light intensities and carbon dioxide concentrations. The combination of 95 μmol $m^{-2} s^{-1}$ and 800 ppm carbon dioxide gave the best results. As has been demonstrated with other cultivars, carbon dioxide enrichment can have a similar effect as increasing the light intensity. For example, growth under 365 ppm carbon dioxide (ambient) and a light intensity of 95 μmol $m^{-2} s^{-1}$ was comparable to the growth obtained under 800 ppm and 55 μmol $m^{-2} s^{-1}$. Therefore, the additional carbon dioxide increased the benefits of supplemental lighting by 42% (Gartner Yrket, 16/1997).

In The Netherlands, 'Festival' cultivars are irradiated with an intensity of 55 μmol $m^{-2} s^{-1}$. In view of what is described above, this does not seem to be optimal. For many cultivars, the flower bud initiation increases significantly over a range of light sums between 4 and 8 mol $m^{-2} d^{-1}$. Bud atrophy simultaneously declines significantly. Although light sensitivity is highly cultivar dependent, the minimum light intensity appears to be 75 μmol $m^{-2} s^{-1}$. With 16 hours of supplemental lighting, an extra light sum of 4.3 mol $m^{-2} d^{-1}$ is obtained. Adding carbon dioxide would increase this by 42% (1.8 mol $m^{-2} d^{-1}$). Therefore, the final effect is comparable to 4.3 + 1.8 = 6.1 mol $m^{-2} d^{-1}$. This is added then to the average natural light sum of 2.3 mol $m^{-2} d^{-1}$ in December, in The Netherlands. The total daily light sum consequently exceeds the desired level of 8 mol $m^{-2} d^{-1}$.



African violet is a shade plant with a low light requirement, belonging to the family of Gesneriaceae. African violets come from Tanzania (Africa), lat. 5°SL. The varieties, used for breeding, grow in the forests of the Usambara mountains under tropical conditions at 18-23°C and an annual precipitation of 1,500-2,500 mm.

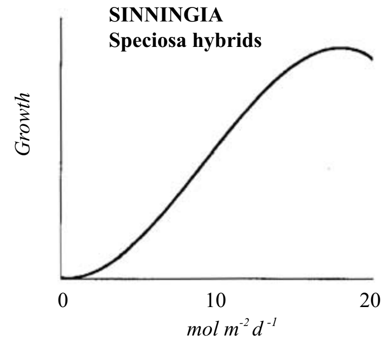
Experiments at the Research Station for Floriculture and Greenhouse Vegetables, in The Netherlands, with the cultivars Rosamini 'Orange' and 'Pink' led to the conclusion that both a longer duration supplemental lighting as well as a higher light intensity will result in a better quality product during winter production (Verberkt, 1997a). Of the various treatments, a 20-hour photoperiod and a light intensity of 45 μmol $m^{-2} s^{-1}$ appeared to be the best combination. The maximal supplemental light sum was 2.8 mol $m^{-2} d^{-1}$ (17.4 hours of supplemental lighting). Plant height increased, as well as the fresh and dry mass of the vegetative parts and flowers and buds while the production period was shortened. The dry matter percentage of the vegetative parts increased linearly with the lighting period, so that these parts become sturdier, while light intensity had no effect on this. Compared with earlier described experiments, the extra light sums are rather moderate. It is, however, obvious that the more light is applied the better it is.

The lighting regime can also affect bud formation (less bud atrophy). It has been observed in the cultivar 'Orange Meillandina' that most flower buds are obtained when lighting is applied in the middle of the night (22:00-04:00 hr) instead of as daylength extension (Hendriks, 1988).

Saintpaulia ionantha (African violet)

African violet is a shade plant and does not need much light for optimum growth. A daytime light intensity of 200-300 μmol $m^{-2} s^{-1}$ is considered optimum for growth and flowering of mature plants, and 100-160 μmol $m^{-2} s^{-1}$ for young plants (Post, 1949; Laurie, 1969). The minimum or threshold value for flower initiation and development was reported as 60 μmol $m^{-2} s^{-1}$ (Stinson, 1954). The minimum light sum therefore is 2 mol $m^{-2} d^{-1}$ (Faust, 1994). The largest number of inflorescences were obtained using a light intensity of 240 μmol $m^{-2} s^{-1}$ and a temperature of 18°C while the largest number of flowers per inflorescence developed at 160 μmol $m^{-2} s^{-1}$ and 27/24°C (Hildrum, 1969). The light sums were 13.8 and 9.2 mol $m^{-2} d^{-1}$, respectively. Lighting was provided for a period of 16 hours with fluorescent lamps.

Above 250 μmol $m^{-2} s^{-1}$, the incidence of chlorophyll damage increased so that leaves became chlorotic and necrotic (Kimmins, 1992). In The Netherlands in February, the shade curtains are already partially closed to prevent flower damage. This is usually done when the light level inside the greenhouse exceeds 200 μmol $m^{-2} s^{-1}$. The plants grown under low light intensities have to adjust gradually to higher light levels. The set point for operating the shade curtain



Sinningia (or gloxinia) has an average light requirement. The plant belongs to the family of Gesneriaceae. The varieties used for breeding originated from the tropical forests of Brazil.

can be slightly increased later in the season. In the fall, when the whitewash has been removed, the shade curtain is closed between a light intensity of 325 and 375 $\mu mol\ m^{-2}\ s^{-1}$ (DLV, 1994).

At light sums between 4 and 8 $mol\ m^{-2}\ d^{-1}$, plants of adequate quality can be grown. The initiation and development of the flowers was significantly stimulated when the light sum exceeds 4.2 $mol\ m^{-2}\ d^{-1}$ (= 100 $klxh\ d^{-1}$ HPS light) or 6.4 $mol\ m^{-2}\ d^{-1}$ (= 100 $klxh\ d^{-1}$ daylight) (Ludolph, 1993). The light responses are highly cultivar dependent. American research indicated a minimum light sum of 4 $mol\ m^{-2}\ d^{-1}$ (Brown-Faust, 1991; Stroemme, 1985).

Before final spacing, most commercial growers agree that lighting during the winter is profitable. However, the benefits of lighting during the final production phase are more and more recognized as well. In The Netherlands, growers provide supplemental lighting from mid-September to the beginning of April. The lamps are turned on as soon as the outside global radiation drops below 50 $W\ m^{-2}$. The minimum required light intensity is 40 $\mu mol\ m^{-2}\ s^{-1}$, with a minimum dark period of 8 hours. If supplemental lighting is provided for 16 hours with an intensity of 40 $\mu mol\ m^{-2}\ s^{-1}$, an extra light sum of 2.3 $mol\ m^{-2}\ d^{-1}$ is realized in The Netherlands, during the darkest weeks of December the total light sum (including supplemental lighting) remains just below the minimum value of 4 $mol\ m^{-2}\ d^{-1}$, while in January, it is above the minimum value. These are low light sums but for certain cultivars (*e.g.* 'Mina') it was demonstrated that (too) high light sums and intensities stimulated undesired multiple shoot formation, especially for a light intensity above 60 $\mu mol\ m^{-2}\ s^{-1}$ (Ludolph, 1993). It had a negative impact on plant form as well. Furthermore, the leaves became harder and broke more easily during shipping (Verberkt, 1995ab).

Positive effects of supplemental lighting were:

- Shorter production time;
- Increase in fresh and dry mass;
- Increase in total leaf number;
- and consequently the total leaf area and total quality, despite the fact that the leaves became more brittle and more sideshoots were formed (Verberkt, 1995ab).

Lighting to a target light sum was compared in experiments at the Research Station for Floriculture and Greenhouse Vegetables, in The Netherlands, with supplemental lighting to a daylength of 20 hours (Verberkt, 1995ab). No distinct differences were observed in fresh and dry mass of the plants. German research demonstrated that African violets respond to the timing of lighting. Lighting before sunrise (04:00 - 10:00 h) or after sunset (16:00 - 22:00 h) resulted in more rapid flowering (Hendriks, 1988).

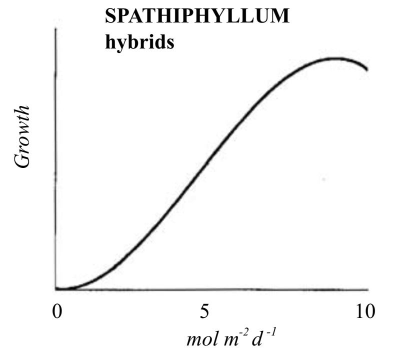
Sinningia cardinalis (Rechsteineria, Gesneria)

During the winter, the effects of supplemental lighting on Gesneria are very positive. When supplemental lighting was provided to increase the daylength to 18 hours using a light intensity of 30 $\mu mol\ m^{-2}\ s^{-1}$, compact plants developed with side shoots that do not require any growth regulators. Without lighting the plants became stretched without multiple shoots (Anon., 1992).

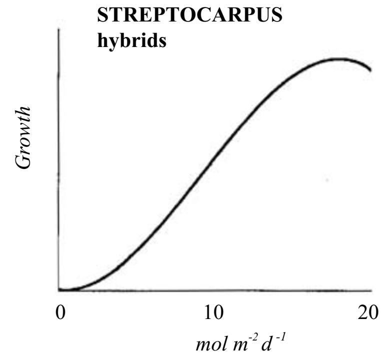
Sinningia Speciosa hybrids

The Gloxinia responds very strongly to supplemental lighting, both in terms of intensity and duration. When supplemental lighting was provided with and intensity of 35 $\mu mol\ m^{-2}\ s^{-1}$ and a 12-hour photoperiod, or with 70 $\mu mol\ m^{-2}\ s^{-1}$ and a 24-hour photoperiod, the plants flower under the latter conditions, while under the former, flower buds are not yet visible (Hendriks, 1993). Growth is linearly related to the light sum provided the plants are grown at optimum temperatures (Sydnor, 1972). The cultivation period, the number of flower buds, and also the number of sideshoots increased with higher light sums (Hendriks, 1993). Larger numbers of sideshoots resulted in a decline of quality, particularly when grown under a 24-hour photoperiod with a light intensity of 70 $\mu mol\ m^{-2}\ s^{-1}$ (resulting in a quality assessment of 2.2 on a scale from 1 to 5).The combination of 24 hours and 35 $\mu mol\ m^{-2}\ s^{-1}$ gave better results, with a quality assessment of 3.0. Gesneria can grown under twice as much light as African violets: 400-500 $\mu mol\ m^{-2}\ s^{-1}$ (Kimmins, 1992). According to German literature, however, their responses were similar (Horn, 1996). Shading should be conducted above a light intensity of 600 $\mu mol\ m^{-2}\ s^{-1}$ (Dole, 1999). In experiments at PBG, The Netherlands, shading was provided at a light intensity between 350 and 480 $\mu mol\ m^{-2}\ s^{-1}$ at plant level. For northern countries during the winter, supplemental lighting is recommended with light intensities between 45 and 70 $\mu mol\ m^{-2}\ s^{-1}$ and a 24-hour photoperiod (Grimstad, 1987; Strømme, 1985).

Adding supplemental lighting with an intensity of 30 $\mu mol\ m^{-2}\ s^{-1}$ to a daylength of 20 hours resulted in short and full plants with many sideshoots, many flowers, and a shorter production period. This intensity is a minimum requirement. The luminaires were turned when outside global radiation drops below 50 $W\ m^{-2}$. When lighting is applied during fixed times of the day, the number of effective lighting hours declines. Since this is at the expense of production, adding supple-



Spathiphyllum has a low light requirement. The plant belongs to the family of Araceae.



Streptocarpus has an average light requirement. It belongs to the family of Gesneriaceae. The hybrids are DN, and their flower development is promoted by high temperatures (Horn, 1996).

mental lighting as soon as the outside global radiation drops below 50 W m^{-2} is preferred. During week 51 doing this resulted in almost 17 hours of supplemental lighting. Due to the positive response to more light during the winter months, the use of light intensities above 30 $\mu mol\ m^{-2}\ s^{-1}$ should be considered. This is also valid for the production phase between seeding and transplanting. German experiments with the cultivar 'Rosa Traum' pointed out that when extra light sums of more than 2.5 $mol\ m^{-2}\ d^{-1}$ are provided, leaf breakage increased. This occurred, for example, at a light intensity of 35 $\mu mol\ m^{-2}\ s^{-1}$ and a 20-hour photoperiod (Hendriks, 1993).

Spathiphyllum hybrids

This plant's natural habitat is the moist, tropical jungle in shaded places. As a result, the light requirement is low. Light levels during production range from 300 to 500 $\mu mol\ m^{-2}\ s^{-1}$ (Griffith, 1998). In the living room they can cope with very low light levels, as low as 20-30 $\mu mol\ m^{-2}\ s^{-1}$ (Griffith, 1998). Lighting improves shoot formation and consequently the bushiness. In some cultivars, such as 'Petite', this response is very strong. The production period is slightly reduced and the leaves become harder. When the light levels used are too high, the position of the leaves (leaf angle) may change and the leaf color may become paler. It is recommended not to exceed a 16-hour photoperiod with a supplemental light intensity of 30 $\mu mol\ m^{-2}\ s^{-1}$. Doubling the light sum in December may result in a considerable increase (30%) in the number of shoots per plant. Even though Spathiphyllum requires only a moderate light quantity, limited supplemental lighting may be highly effective.

Streptocarpus hybrids

Streptocarpus needs more light than the African violet. It responds strongly to supplemental lighting. During the winter in the northern latitudes, a minimum light intensity of 100 $\mu mol\ m^{-2}\ s^{-1}$ is recommended (Strømme, 1985). The effect of lighting with lower intensities has been tested at the Research Station in Aalsmeer, The Netherlands (Verberkt, 1995b). Using supplemental lighting for a 20-hour photoperiod and a light intensity of 30 $\mu mol\ m^{-2}\ s^{-1}$, the fresh and dry mass of the plants increased, and the production period was shortened. Additional lighting to reach a target light sum resulted in less heavy plants compared to adding supplemental lighting based on outside light levels. A target light sum of 3 $mol\ m^{-2}\ d^{-1}$ should be obtained during the darkest weeks of December and January. The highest level achieved with this strategy was 9.2 $mol\ m^{-2}\ d^{-1}$ in week 37.The question, however, is what minimum light sum is required. For flowering, at least 240 $\mu mol\ m^{-2}\ s^{-1}$ is required (Kimmins, 1992). In The Netherlands, this daily average is obtained in March at a light sum of about 10 $mol\ m^{-2}\ d^{-1}$. It is therefore preferred to use higher light intensities than 30 $\mu mol\ m^{-2}\ s^{-1}$. These light levels in March correspond with the target values for the production of Streptocarpus: 200-400 $\mu mol\ m^{-2}\ s^{-1}$ (Amoine, 1985). A set point for shading of 600 $\mu mol\ m^{-2}\ s^{-1}$ was reported to avoid leaf burning due to excessive leaf temperatures (Heide, 1967). With 30-50% shade, the previously mentioned target values can be achieved.

Light levels and lighting

Table 6.8 shows the desired light levels for different flowering pot plants grown in the greenhouse (various sources). The target light levels for The Netherlands can be found by investigating the light set points for (automatic) shading. In many pot plant crops, shading is used to avoid high temperatures and/or excessive light intensities.

Flowering pot plants are grown using the highest light levels possible because it benefits both production (dry matter accumulation and reduction of production time) and the keeping quality.

The minimum levels necessary to keep the plants in good shape in the consumer's living room are often based on experience. Comparing the natural light in the greenhouse (Table 5.3) and the desired light levels for the various crops (Table 6.8) gives insights into the best production method. The required light sums are shown as much as possible in the graphs accompanying the lighting recommendations for the various crops. Finally, the minimum light levels required at the consumer's living room are shown in Table 6.9.

***Table 6.8.* Recommended light intensities for growing of various flowering pot plants.**

This data originates in the United States (columns 1 and 2) and Germany (column 3).

Column 1:
Original data in footcandles, converted to µmol m^{-2} s^{-1} using a conversion factor of 0.20 (Thimijan and Heins, 1983).
1,000 ft-c = 200 µmol m^{-2} s^{-1} (solar radiation)
Source: Roy Larson, 1992.

Column 2:
These values have been derived and adjusted from: Conover, 1991; Conover and McConnell, 1981; Vladimirova et al., 1997.
1,000 ft-c = 200 µmol m^{-2} s^{-1} (solar radiation)
Source: John Dole and Harold Wilkins, 1999.

Column 3:
Source: Wolfgang Horn, 1996.

	PPF µmol m^{-2} s^{-1} 1	PPF µmol m^{-2} s^{-1} 2	PPF µmol m^{-2} s^{-1} 3
Aechmea	-	-	450
Anthurium spp.	-	200-400	-
Aphelandra squarrosa	200-300	200-300	> 550
Begonia Elatior	300-400	300-400	-
Calceolaria	-	< 1000	-
Chrysanthemum	*sh.t.h*	*sh.t.h* *	-
Cyclamen	-	< 800	< 600
Euphorbia pulcherrima	800-1,200	700-1,200	-
Exacum	*sh.t.h*	*sh.t.h.*	-
Gerbera	-	*sh.t.h*	-
Guzmania	-	-.	250
Hibiscus	*sh.t.h*	*sh.t.h*	-
Hydrangea	-	*sh.t.h*	-
Kalanchoe	-	*sh.t.h.* < 1,160	-
Nidularium	-	-	350
Pelargonium zonale	600-1,000	700-1,000	450-625
Pelargonium peltatum	350-700	500-600	-
Pelargonium grandiflorum	> 700	-	-
Pelargonium (seed)	600-1,000	700-1,000	450-625
Phalaenopsis	-	240-400	veg. 300
Rosa	-	*sh.t.h*	-
Saintpaulia (African violet)	190-250	200-300	200
Sinningia	350-500	400-600	200
Spathiphyllum**	300-500	-	-
Streptocarpus	230	200-400/600	300

**   sh.t.h: no light limit, only shading to avoid excessive temperatures*
*** derived from Lynn P. Griffith, jr.*

***Table 6.9.* Minimum light levels for flowering pot plants under living room conditions.**

Column 1:
Required light intensity for durable interior plantings
10>50 indicates at least 10 but preferably more than 50 µmol m^{-2} s^{-1}
The original values were given in lux. The conversion into µmol m^{-2} s^{-1} was based on:
1,000 lux = 18 µmol m^{-2} s^{-1}
Source: FFL Richtlinie Fassadenbegrünungen, 1995, Bonn.

Column 2:
Based on empirical data. The original values were presented in lux. The conversion into µmol m^{-2} $s^{-1}$was based on:
1,000 lux = 18 µmol m^{-2} s^{-1}
Source: Wolfgang Horn, 1996.

Column 3:
Based on empirical data.
40 >160 indicates at least 40, but preferably more than 160 µmol m^{-2} s^{-1} to maintain color or some growth or flowering.
Source: Lynn P. Griffith, Jr., 1998.

	PPF µmol m^{-2} s^{-1} 1	PPF µmol m^{-2} s^{-1} 2	PPF µmol m^{-2} s^{-1} 3
Anthurium andreanum	20 >75	15	100
Aphelandra squarrosa	20-75	-	30-50
Begonia Elatior	50 >75	20	-
Bromeliaceae	50 >75	15	40 >150
Campanula isophylla	-	15	-
Chrysanthemum	50-75	10	-
Columnea microphylla	50 >75	15	-
Cyclamen persicum	20-75	20	-
Euphorbia pulcherrima	50-75	20	-
Hibiscus rosa-sinensis	50-75	20	-
Kalanchoe blossfeldiana	50-75	20	-
Saintpaulia ionantha	10-75	15	40 >160
Spathiphyllum wallisii	10-75	10	20-30
Streptocarpus hybrids	50 >75	15	-

6.2 Lighting Recommendations for Various Crops

6.2.6 Lighting of cut flowers

Classification
This classification is based on light requirements:

I. **Very high light: 30-50** mol m^{-2} d^{-1}:
Alstroemeria, Aster, Chrysanthemum, Dianthus, Eustoma, Gladiolus, Asiatic lily, Oriental lily hybrids, Rosa, Trachelium

II. **High light: 20-30** mol m^{-2} d^{-1}:
Bouvardia, Gerbera, Iris, Lilium longiflorum, Zinnia

III. **Medium light: 10-20** mol m^{-2} d^{-1}:
Freesia

IV. **Low light: 5-10** mol m^{-2} d^{-1}:
Hyacinthus, Narcissus*, Tulipa**

* *during forcing*

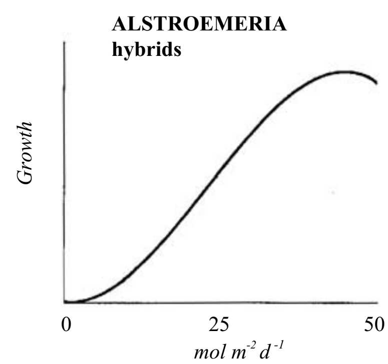
A remarkably high number of cut flower species belong to the first category exhibiting very high light requirements.

Alstroemeria hybrids

The current cultivars of the Inca lily are developed from crossbreeding (Stapel-Cuijpers, 1995). The wild cultivars are native of South America, more specifically from central Chile and South-East. The cultivars from Chile, which were used for breeding are characterized by big, orchid-like flowers. In addition, they often have small, narrow leaves with poor keeping quality. The cross parent from Brazil (*A. pulchella*) has wider leaves with better keeping quality, but its flowers are smaller and do not open as wide (Bayer, 1987).
Alstroemeria is a quantitative LD plant with a critical daylength of 12 to 13 hours. Flower initiation is not only promoted by lower temperatures but also by long days. Under these conditions, vegetative shoots start with flower initiation earlier, and the number of internodes below the inflorescence declines. Usually, flowering takes place during the spring, when daylength, temperature and light sum are optimal.

Daylength
Daylengths of more than 14 to 16 hours are generally not recommended. Experiments pointed out that shoot production and number of flower clusters per stem declined under increasing daylengths (Vonk Noordegraaf, 1981). Currently, however, several cultivars appear to flower year-round at daylengths of 20 hours and high light sums (Bakker, 1995; Baevre, 1997). It is recommended that, in The Netherlands with its relatively low light intensities, the daylength should be no more than 12 to 13 hours, to avoid a decline in shoot growth (DLV, 1998).

6.2.6 LIGHTING OF CUT FLOWERS
- ***Alstroemeria***
- ***Aster Universum Group***
- ***Bouvardia***
- ***Chrysanthemum***
- ***Dianthus caryophyllus***
- ***Eustoma (Lisianthus)***
- ***Freesia***
- ***Gerbera***
- ***Gladiolus***
- ***Hyacinthus***
- ***Iris (Dutch)***
- ***Lilium***
- ***Narcissus***
- ***Rosa***
- ***Trachelium***
- ***Tulipa***
- ***Zinnia***



Alstroemeria (Inca lily) is a quantitative LD plant with a critical daylength of 12-13 hours. The flower initiation and development are stimulated by LD (about 13 hours), while shoot initiation is only slightly inhibited. Besides daylength, the temperature near the roots (rhizomes) has an important influence on (primary) flower initiation. A cold period (vernalization) at 12 to 16°C stimulates flower initiation in many cultivars, which in combination with long days and high light sums, provides the basis for year-round production. Some cultivars are not affected by soil temperature, while others react positively to higher soil temperatures. Photoperiodic lighting and temperature can be used to influence shoot production. LD (16 hours) reduces the number of shoots, bud abortion, while it advances flowering. Bud blast is not prevented by photoperiod lighting, but through supplemental lighting. The light requirement is very high.

Dormancy occurs when visible shoot growth is largely or completely absent under long days and very low temperatures. Under such conditions, strong generative development and rhizome formation take place. Dormancy is avoided by high temperatures and short-day, but these factors adversely affect flower initiation (Stapel-Cuijpers, 1995).

Soil temperature

Some cultivars require the root temperature below 14-16°C for flower initiation, while others have a neutral or even a positive response to higher soil temperatures (Bakken, 1999). A general recommendation is that the soil should be cooled more when the plants experience an increase in shoot initiation or in case that too many blind shoot develop.

For the cultivars 'Diamond' and 'King Cardinal', the production of flowering stems stop at soil temperatures of 20°C and higher. For these cultivars and for 'Yellow King', 'Pink Triumph', and the Butterfly types, the target soil temperature is 13°C, while for 'Ibiza', 'Lambada' and 'Rebecca' it is about 15°C. For the cultivars 'Ballet' and 'Sacha', a soil temperature of 16-17°C is recommended.

Light intensity and light sum

Another important growth factor is light. Alstroemeria has a very high light requirement. For *e.g.* the cultivar 'Jacqueline', crop photosynthesis saturates at a very high light intensity of 1,200 μmol m^{-2} s^{-1} and an ambient carbon dioxide concentration (Leonardos, 1994). Therefore, the greenhouses should have high light transmission. In summer, some shading is applied to prevent (too) high soil temperatures. However, this is at the expense of production. In The Netherlands, the rate of crop photosynthesis for plants grown inside the greenhouse is hardly ever saturated. The carbon dioxide concentration is the limiting growth factor during summer production. Bud blast beyond the summer months is believed to be caused primarily by low light sums.

Converting instantaneous light levels and light sums

*For **high-pressure sodium** (SON-T Plus 400 W) light:*
1 μmol $m^{-2}s^{-1}$ = 85 lux = 0.2 Wm^{-2} PAR = 7.9 ft-c (1)

For the conversion of lux to footcandle: 1 ft-c = 10.76 lux
For lux and ft-c as basis, the conversions are:
1,000 lux = 11.8 μmol m^{-2} s^{-1} = 2.4 W m^{-2} PAR = 92.9 ft-c
1,000 ft-c = 126.6 μmol m^{-2} s^{-1} = 25.3 W m^{-2} PAR = 10.76 klux

Measurements by the Research Station for Floriculture and Glasshouse Vegetables in Aalsmeer, show variations from 11.9 to 13.4 μmol m^{-2} s^{-1} per 1 klux.
The number of μmol m^{-2} s^{-1} per klux increases as the lamps get older and the lamp voltage is increased.

*For **daylight**, the following conversion can be used:*
1 μmol $m^{-2}s^{-1}$ = 56 lux = 0.217 Wm^{-2} PAR = 5.2 ft-c (2)
For lux and ft-c as basis, the conversions are:
1,000 lux = 17.9 μmol m^{-2} s^{-1} = 3.9 W m^{-2} PAR = 92.9 ft-c
1,000 ft-c = 192.3 μmol m^{-2} s^{-1} = 41.8 W m^{-2} PAR = 10.76 klux
The type of weather plays an important part in this conversion, see Table 5.2

Light sum using HPS
1 MJ m^{-2} PAR = 5 mol m^{-2} = 118 klxh = 10,970 ft-ch ***(3)***

Daylight sum *(45% PAR of total radiation)*
1 MJ m^{-2} PAR = 4.6 mol m^{-2} = 71.9 klxh = 6,640 ft-ch ***(4)***

Installed lamp capacity and resulting light intensity of *SON-T Plus 400 W. Source: Maaswinkel, 1996.*
1 lamp for every 18 m^2 of floor area results in:
5.8 W m^{-2} (PAR) or
29 μmol m^{-2} s^{-1} or
2,465 lux or
229 ft-c
1 lamp for every 9 m^2 of floor area results in the double, e.g.
11.6 W m^{-2} (PAR)

Supplemental lighting

Norwegian research has indicated that when the artificial light sum is raised (from 8 to 13 mol m^{-2} d^{-1}), the production increases as well (Bakken, 1999). At the light sum of 13 mol m^{-2} d^{-1}, the average light sum in Dutch greenhouse at the beginning of April, total stem yield is highest when the light sum is spread over a daylength of 20 hours. At a root temperature of less than 14°C, the cultivars 'Diamond', 'King Cardinal' and 'Libelle' flower continuously, just like under 14 and 16 hour photoperiods and lower light sums. The 13 mol m^{-2} d^{-1} light sum was reached using a supplemental light intensity of 176 μmol m^{-2} s^{-1} for a period of 20 hours. The lamps were turned off at an outside global radiation of 250 W m^{-2}. The use of longer photoperiods (16 and 20 hours) is, however, questionable because shoot formation is to be inhibited at photoperiods beyond 14 hours.

In a number of cultivars, flower abortion is frequently observed during fall and winter, including 'Little Sun', 'Virginia', 'Soleil', 'Helios', 'Victoria', 'Libelle' and 'Cobra' (DLV, 1998). Even though modern year-round flowering cultivars are less sensitive to abortion, lighting is recommended. This accelerates the development of initiated flowers, increases the number of new shoots, and particularly yields heavier stems, which do not suffer from bud blast. The rhizomes continue to split off shoots during the winter over a longer period, and shoots are of a better quality. This was the conclusion from experiments conducted at the PBG (The Netherlands) using a light intensity of 60 μmol m^{-2} s^{-1} and a 14 hour photoperiod from week 37 to week 4, followed by a 12 hour photoperiod through week 12 with photoperiodic lighting (1-2 μmol m^{-2} s^{-1}). Cultivars such as 'Helios', 'Wilhelmina', 'Victoria', 'Cobra', and 'Jubilee' did not show any after-effects (*e.g.* bud-blast (Uitermark, 1997).

Photoperiodic lighting

Photoperiodic lighting can be applied continuously or cyclically as daylight extension or night interruption. Continuous lighting and night interruption have a stronger effect. Choosing which treatment to use depends on cultivar and growing system. Generally for cultivars, which produce many shoots after the summer with a high rate of abortion and light stems, the daylength can be extended to 14 hours with ordinary incandescent lamps at an installed lamp wattage of 15 W m^{-2}, combined with cyclic lighting for 10 minutes every half hour (using a light intensity of 1 μmol m^{-2} s^{-1}). When using compact fluorescent lamps, lighting is provided either at least 10 minutes every half hour or continuously, providing night interruption (from midnight onwards) or daylength extension, particularly with vigorous cultivars. The longer the daylength, the more shoot formation declines. Thus, the stems that do grow out get more sugars from the limited total amount of available sugars, resulting in reduced flower abortion and improved quality. Simultaneously, the roots can build up more reserves, which may be useful during the winter. As a result, the spring harvest will start on time.

When cooling is applied, usually lighting is not necessary because the shoot growth is sufficiently inhibited. Photoperiodic lighting can be provided during spring and fall. During spring, lighting is applied on young fall plantings and 2 or 3-year old crops. Renewal of shoot growth is improved while flowering is advanced. Lighting is applied on well-growing crops (three to four shoots developing per plant every 10 days), usually at the end of December or the beginning of January. Following this recommendation, a reduction of production time of two to four weeks is possible. Lighting is stopped when natural daylength reaches 13 hours, or when the number of newly formed shoots becomes too low. Fall lighting begins in late summer to promote the initiation and development of flower buds. Due to the reduced number of blind shoots, the production in late fall, winter and spring is higher. Moreover, less labor is required for thinning. The desired daylength is about 14 to 16 hours.

When the plants produced four shoots per week (after mid-July), 90 minutes of lighting was recommended. The lighting period could subsequently gradually be extended with 15 minutes every week after 1 August (DLV, 1999). The fuller the crop, the longer the lighting period should be. Night interruption results in shorter stems, while the number of florets per umbel declines. During fall, the (soil) temperatures drop. When soil temperature drops below 15°C, the photoperiod should be reduced to 13-14 hours for certain cultivars, to avoid inhibition of new shoot initiation. Photoperiodic lighting does not affect the year-round cultivars.

Growth factors

In The Netherlands, the supplemental light intensity is usually 50-60 μmol m^{-2} s^{-1}. According to the DLV (1999), 50 μmol m^{-2} s^{-1} for 10 hours provides just enough light energy (1.8 mol m^{-2} d^{-1} for crop maintenance. Therefore, this light intensity is too low for quality crop production. This was also apparent from research in Scandinavian countries where electricity is much cheaper. As for other crops, besides an optimum light environment, other production factors are equally important: soil and air temperature, water and nutrient supply, and aerial carbon dioxide concentration. The production can be increased by 16% using carbon dioxide enrichment, while supplemental lighting on its own achieved an increase of only 7%. Supplemental lighting and carbon dioxide combined increased production by 31%.

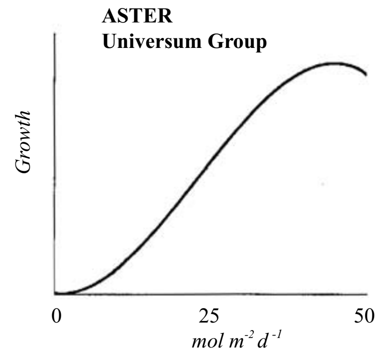
Recommended supplemental lighting

The general advice is to use the narrow-angled (deep) reflectors unless the height above the crop (mounting height) is less than 2 meters. The maximum photoperiod is 16 hours, and is gradually reduced to 11-12 hours on 1 January. This could be achieved by shortening the photoperiod every two weeks with 30 minutes (DLV, 1999). Subsequently, daytime lighting can be continued for a number of weeks. This is particularly desirable for cultivars such as 'Flamingo', which produce very few shoots after a winter of lighting, or for cultivars, which are becoming too short in spring (*e.g.* 'Granada'). Cultivars with more leaf area and length such as 'Virginia' and 'Diamond' can be lit through mid-February to a maximum photoperiod of 12-13 hours. The lamps are turned on when the outside global radiation drops below 100 W m^{-2}. Lamps are turned off as soon as the outside global radiation reaches a level of 150 W m^{-2} (DLV, 1998). With a maximum photoperiod of 12 hours and a light intensity of 50 μmol m^{-2} s^{-1}, an additional light sum of 2.2 mol m^{-2} d^{-1} can be provided. Including the natural light sum, this results in a total light sum of 4.5 mol m^{-2} d^{-1} (2.2 + 2.3). This is low compared to the artificial light sum used in Norwegian research (Bakken, 1991): 13 mol m^{-2} d^{-1}. The application of lighting with a higher intensity such as 60 μmol m^{-2} s^{-1}or more, should therefore be considered. As a result, the photoperiod can be slightly extended. The required light sums are cultivar dependent, just like the corresponding outside global radiation levels used for turning the lamps on or off (100-150 W m^{-2}). From a physiological point of view it is perhaps better to increase these set points.

Summarizing the benefits of supplemental lighting on Alstroemeria:

- Increase in production; 1,600 hours of lighting a year with an intensity of 50 μmol m^{-2} s^{-1} yielded 10% more stems of 'Flamengo' and 'Victoria' (Benninga, 1999).
- Improvement of quality; increase in numbers rated top quality; improved keeping quality; more five-headers (cymes) instead of three-headers (cymes) without lighting; the flower color becomes more intense while the leaves get slightly smaller.
- Shifting production to a period with higher prices.
- Relief of labor peak during spring.
- Reduction of flower bud abortion, especially for the cultivar 'Virginia'.
- Reduction of Botrytis infection.

Year-round production is possible through a combination of soil cooling during the summer and supplemental lighting during the winter for many cultivars.



Aster is a quantitative SD plant. The critical photoperiod for flower initiation and formation is approximately 15 hours. For flower development, a photoperiod of 12.5 - 13 hours is needed. During the vegetative period, a 17-hour photoperiod is maintained.
The light requirement is very high (higher than that of chrysanthemum). At high light intensities, the rate of photosynthesis is very high. Therefore, plant growth during the winter is slowed down considerably under low light intensities.
As with chrysanthemum, a LD treatment is provided initially to prevent flower bud initiation until a stem length of about 50 cm is reached. Then, the SD treatment can be started.
For the LD treatment, photoperiod lighting with incandescent, (compact) fluorescent, or low-pressure sodium lamps are all equally effective. Aster is more sensitive to photoperiod lighting than chrysanthemum. A light intensity of about 0.4 µmol m^{-2} s^{-1} is sufficient.

Aster Universum group

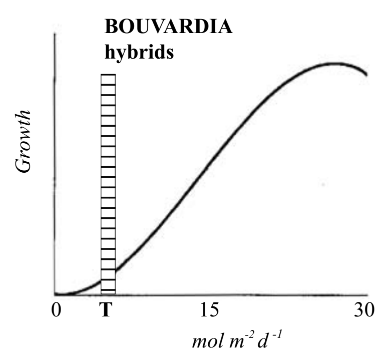
A very successful cultivar belonging to the Universum group is 'Monte Cassino', formerly named *A. ericoides*. This group of cut asters are hybrids, originating from crosses between *A. novi-belgii, novae-angliae, alpinus, amellus, cordifolius, dumosus, lateriflorus* and others (Hetterscheid, 1995). Aster is a quantitative SD plant with a critical daylength of about 15 hours for flower initiation. For quick flower development, a shorter daylength is necessary (12.5-13 hours).
Asters are provided supplemental lighting during the LD phase to a photoperiod of 20 hours, while during the SD phase up to 11-11.5 hours with a light intensity of 32 µmol m^{-2} s^{-1}. As a result, the production increases with 10%, while the quality improves due to higher stem weight and better flower bud development. Without supplemental lighting, asters cannot be grown during the winter in The Netherlands.
Experiments at the PBG showed that during the winter months, bud development and quality can be improved by extending the daylength to 13.5 hours in at least the first five weeks of the SD period (Durieux, Blacquière, 1997). This delays flower initiation and development, so that more flowers can develop at the same time without abortion. When all flower parts in most of the flower buds have been initiated, the daylength is cut back to 11 hours. This approach is a very good alternative to interrupted lighting in which the SD treatment is interrupted with several days of LD treatment. As is the case with interrupted lighting, the production period increases with eight to eleven days when the daylength is extended to 13.5 hours. The effects are cultivar dependent, but the quality in December-February remained poor without supplemental lighting (Krijger, 1999).

Bouvardia hybrids

Bouvardia is a qualitative SD plant requiring a dark period of 13-14 hours for flower bud initiation. To obtain flowering during the summer, blackout shading is applied. It is a high light requiring crop that, in The Netherlands during low-light months, produces short and thin flowering stems as well as many blind shoots. However, these blind shoots are frequently long and firm. Both quality and production are improved by supplemental lighting. During the vegetative phase it is possible to use an 18-20 hour photoperiod, and 10-11 hours during the generative phase. During experiments, attempts have been made to reduce the number of blind stems using supplemental lighting, and, consequently, raise the yield. This appeared possible by lighting only during the first week of the SD treatment (seven times 11 hours). Then induction and initiation of the inflorescence takes place. As in other crops, these processes require a large amount of (light) energy.
As soon as the outside global radiation drops below 300 J cm^{-2} d^{-1} after the beginning of the SD treatment (1-2 weeks), the percentage blind shoots rises. Therefore, this light sum is a minimum requirement for the development of blind shoots. Inside the greenhouse, this minimum requirement corresponds with

80-90 J cm^{-2} d^{-1}PAR, or 3.7 to 4.1 mol m^{-2} d^{-1}.

In The Netherlands, during the period from mid-November through the last week of January the light sum is below this threshold value. The percentage of blind shoots declined with an increase in light intensity. A light intensity of 54 µmol m^{-2} s^{-1} had slightly



Bouvardia is a SD plant.
*The threshold value (**T**) for bud abortion is between 3.7 and 4.1 mol m^{-2} d^{-1}.*
The light requirement is high.

more effect than an intensity of 35 µmol m^{-2} s^{-1}, and eliminates virtually all flower bud abortion (blind shoots).
Flowering at the higher intensity of 54 µmol m^{-2} s^{-1} was also more uniform. The extra stems fell almost all in the highest length category of 70-80 cm, which demand the highest prices. Using this intensity proved successful if the mobile lighting equipment was used six times between weeks 46 and 52, and another four times during January (De Hoog, 1995).
By providing supplemental lighting in December for 11 hours at a light intensity of 54 µmol m^{-2} s^{-1}, an additional light sum of 2.1 mol m^{-2} d^{-1} is added. In The Netherlands, the average total light sum is then:

4.4 mol m^{-2} d^{-1} (2.3 natural light + 2.1 artificial light).

Thus, the **threshold value** for blind shoot development (3.7 to 4.1 mol m^{-2} d^{-1}) is exceeded. During December, there are days with less than 2.3 mol m^{-2} d^{-1} of natural light, and lighting with a light intensity of 35 µmol m^{-2} s^{-1} is slightly deficient in order to prevent the development of blind stems. Consequently, a minimum level of 54 µmol m^{-2} s^{-1} was deemed more appropriate (De Hoog, 1995). Experiments in commercial greenhouses with a mobile lighting installation providing a light intensity of 70-75 µmol m^{-2} s^{-1} during the first week of the SD treatment, supported this conclusion (Van Leeuwen, 1995). According to grower survey, an average supplemental light intensity of 30 µmol m^{-2} s^{-1} is commonly installed (De Hoog, 1996). Only three growers applied twice this intensity. Two-thirds of them use a mobile lighting installation only during the SD treatment. Some growers provide lighting for seven days at 11 hours a day, others 12 to 14 days in order to further suppress the percentage of blind stems. The advantages of using supplemental lighting mentioned were:

- A more uniform harvest resulting in labor savings,
- Longer stems, which used to be blind, can now be harvested,
- Crop color is better than that of an unlit crop.

Chrysanthemum

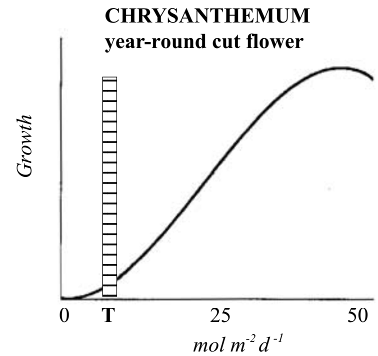
Chrysanthemum has a high light requirement. There are, however, variations among cultivars. Under Dutch conditions, vegetative and generative growth (flower bud initiation) is delayed from mid-August to mid-April (Klapwijk, 1986). Lighting can significantly improve crop quality during that period. Optimum vegetative growth occurs at light sums above 375 J cm^{-2} d^{-1} PAR or 17.3 mol m^{-2} d^{-1} inside the greenhouse. At this light sum, the average light intensity inside the greenhouse is about 345 µmol m^{-2} s^{-1} (14 hour photoperiod). For minimum vegetative growth and a limited delay in flower bud initiation during the winter, light sums of 100 to 150 J cm^{-2} d^{-1} PAR or 4.6-4.9 mol m^{-2} d^{-1} at canopy level are needed (Langton, 1992). This can be achieved with a supplemental lighting intensity of about 60 µmol m^{-2} s^{-1}. During the vegetative phase in the winter months, a 20-hour photoperiod can be used (Maaswinkel, 1996) and during the generative phase a 12-hour photoperiod. The latter photoperiod is cultivar dependent, and during non-winter months, the photoperiod is reduced to a maximum of 11 hours. Using a 20-hour photoperiod, an additional light sum of

20 hours x 60 µmol m^{-2} s^{-1} = 4.3 mol m^{-2} d^{-1}

can be realized and during the generative phase:

12 hours x 60 µmol m^{-2} s^{-1} = 2.6 mol m^{-2} d^{-1}.

In The Netherlands and in December, the average light sum inside the greenhouse is 2.3 mol m^{-2} d^{-1}. Therefore, during the generative phase, the total light is: 4.9 mol m^{-2} d^{-1} (2.6 + 2.3), which guarantees continued flower bud initiation, even on days with light sums less than 2.3 mol m^{-2} d^{-1}.
Using 20 hours of lighting during the vegetative phase, the total light sum can be brought to 6.6 mol m^{-2} d^{-1} (2.3 + 4.3). This brings the light sum well above the absolute minimum of 4.6 mol m^{-2} d^{-1} required for vegetative growth. As a result, especially during this stage, production time can be reduced. Furthermore, supplemental lighting has a positive effect on the quality of the plants. The stems are firmer, have shorter internodes and slightly stronger leaves. Research showed that using a supplemental light intensity of 50 µmol m^{-2} s^{-1} increased production by almost 15% by increasing the rotation rate from 4.5 to 5.0 and the plant density from 40 to 45 plants per square meter using the cultivars 'Reagan Wit en Sunny' (Roelofs, 1999). For comparison it is interesting to see what is recommended in Norway: 120 µmol m^{-2} s^{-1}, 18°C, and 800 ppm CO_2 (Gartner Yrket 6/1997). This light intensity provides a light sum of about 5 mol m^{-2} d^{-1} during the



Year-round chrysanthemum is a quantitative SD-plant. The critical daylength is between 10 and 12 hours. Most cultivars require a photoperiod of 11 hours from March to October. For vegetative growth, a daylength of 16 hours or more is needed.

To improve the quality, SD interruption is given during fall and winter. Alternatively, when using supplemental light during the SD period, the photoperiod of fast responding cultivars can be extended from 11 to 12 hours or sometimes more.

*The **threshold values** (T) for quick flower initiation and vegetative growth are between 4.6 and 6.8 mol m^{-2} d^{-1}. The crop has a very high light requirement.*

SD treatment (approximately 11.5 hours). In summary, the positive effects of lighting are:

- Higher production as a result of higher plant density and shorter production period.
- Improved quality of flowers, stems, and leaves.
- Reduced susceptibility to fungal diseases, and, thus, reduced pesticide use.
- Larger range of cultivars available during the winter, with more colors (pink and orange).
- Better planning so that production period is less dependent on the weather.
- Improved possibilities for year-round supply.
- Labor requirement is more uniform.
- Improved competitive position.

Many calculations demonstrate that, economically, little profits are gained from using supplemental lighting. Nevertheless, the acreage equipped with supplemental lighting is growing. It is therefore clear that the advantages listed above, are decisive (Vernooy, 1996).

Photoperiodic lighting

If no supplemental lighting is used, photoperiodic lighting is necessary to keep these SD plants vegetative. Photoperiodic lighting requires a photoperiod of 15-16 hours. Commercial growers use nighttime interruption (cyclic lighting) with incandescent lamps between 23:00 and 04:00 hr, or from 22:00 to 05:00 hr. Using a six-hour nighttime interruption (*e.g.* from 22:00 and 04:00 hr, or from 23:00 to 05:00 hr), the most sensitive period, according to Dutch research data, is during the ninth, tenth and eleventh hour of the dark period, or between the fourth and eighth hour according to British research. This means that the nighttime interruption can be started after midnight, if the night begins at 18:00 hr. After the night break, the remaining dark period cannot be more than eight hours to prevent flower initiation (based on British research). However, commercial growers usually maintain 4-5 hours. Cut flower growers usually provide 6-7.5 minutes of light during each half hour. This is just as effective as continuous lighting.

Lighting intensities of 75 to 100 lux (1.5 - 2 μmol m^{-2} s^{-1})

Installed wattage of incandescent lamps (150 W) and resulting light intensities at 2 m below the lamps. ***Source: PBGA, 1996.***

Light intensity (average) μmol m^{-2} s^{-1}	*Installed lamp wattage watt per 10 m^2*	*Number of lamps per 10 m^2 of floor area*
0.5-1.0 (0.75)	6.4	0.43
1.0-1.5 (1.25)	10.7	0.71
1.5-2.0 (1.75)	15.0	1.00

To obtain the same light intensities using 18 W compact fluorescent lamps, four times as many, and using 18 W fluorescent and low-pressure sodium lamps, three times as many lamps must be installed. For the cultivars 'Majoor Bosshardt' and 'Cassa', a maximum delay of flower initiation was obtained with a light level of 0.7 μmol m^{-2} s^{-1}, using incandescent, compact fluorescent, or low-pressure sodium lamps. Using white fluorescent lamps, an intensity of 1.5 μmol m^{-2} s^{-1} was needed.

Quality improvement

To improve the quality of chrysanthemums grown during fall and winter, the SD treatment is interrupted after about 16 days with 1-13 days of LD treatment using photoperiod lighting. When supplemental light is applied, the SD interruption can be replaced by extending the daylength a little during the SD treatment, starting in October with 5 minutes per week. The photoperiod of fast responding cultivars can be extended from 11 to 12 hours or sometimes more. Starting 1 March, the photoperiod should be reduced to 11 hours through adjustments made during January and February. An alternative strategy may be (as with Aster) to light in three phases: 20 hours during the vegetative phase, 11 hours during the first two to three weeks of the SD treatment, and 12-12.5 hours after flower bud initiation to promote proper flower development (Mol, 1999).

are used for this night break. For commercial production, one 150 w incandescent lamp is installed for each 9.6 m^2 of floor area (approximately 15 (lamp) watt per m^2 of floor area). The light sum maintained during regular production usually lower than for stock plant production. For better production, the light sum for stock plants is almost twice as high. These larger light sums are obtained with higher light intensities and longer lighting periods.

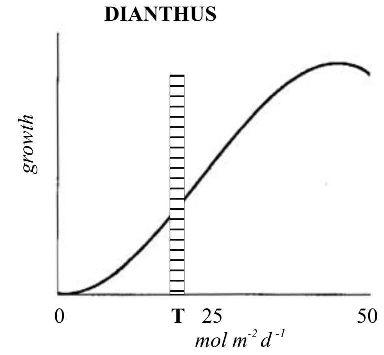
The light sum provided with incandescent lamps during cyclic lighting, can also be applied with high-pressure sodium lamps. If these lamps provide an intensity of 3,230 lux or 38 μmol m^{-2} s^{-1}, the lighting period in the middle of the night does not have to be more than 6 minutes and 16 seconds. This represents a light sum of 14,288 μmol m^{-2} d^{-1} per night (Blacquière, 1999). This is high compared with the cultivar 'Majoor Bosshardt' for which 8,000 μmol m^{-2} d^{-1} proved sufficient (Blacquière, 1988). For the control, incandescent lamps were used with a light level of 1.7 μmol m^{-2} s^{-1}, during 7 hours at ten minutes for each half-hour. The same light sum of 14,288 μmol m^{-2} d^{-1} was applied. Good results were obtained with this strategy in combination with an end-of-September planting. Due to the absence of incandescent lamp light containing more far-red radiation, the quality of the stems was good. The stems were somewhat firmer, with shorter internodes and slightly sturdier leaves. The second experiment, started in early January, pointed out that when SON-T lamps were also used during the day, too much red and too little far-red light is provided. This made the plants less sensitive to night interruption. The cultivar 'Alfa' was generative already at the beginning of the SD treatment, 'Reagan' was not. During a third experiment unexpected developments occurred. The conclusion was that six minutes of nighttime interruption with high-pressure sodium lamps is not (yet) recommended.

Dianthus caryophyllus; standard or spray carnation

Carnations are quantitative LD plants with a high light requirement. Growth ceases at light intensities below 120 µmol m^{-2} s^{-1} (Uitermark, 1987). In The Netherlands, the average light intensity in the greenhouse is below this value from mid-November to mid-January (Table 5.3). As the light sum decreases, the length of the flower stems increases, either as a result of more leaf pairs below the flower bud, or through longer internodes. Low temperatures during winter can prevent the incidence of long, thin, and weak stems. To maintain sufficient crop growth rate (particularly in the period from pinching to flower initiation), in The Netherlands supplemental lighting should be provided from September until mid-April (Klapwijk, 1986). The target light intensity is 385 µmol m^{-2} s^{-1}. This average is reached in The Netherlands when the light sum in the greenhouse is approximately 20 mol m^{-2} d^{-1}. These values are far too high (too expensive) to reach with supplemental lighting during the production period. Photoperiodic lighting is provided frequently during production, because flower bud initiation takes place more quickly with an increase in photoperiod; a so-called quantitative effect. Carnations flower sooner at a daylength of 16 hours compared to 8 hours. This is related to the fact that the number of leaf pairs underneath the flower bud declines with an increase in daylength. The critical photoperiod is 14 hours (Blacquière, 1999). This photoperiod partly depends on the light sum. Using a high light sum, the critical photoperiod decreases and with a low light sum, it increases. During the winter, light levels are so low that daylength extension hardly results in flower initiation. During the summer, the light sum is so high that the daylength becomes irrelevant.

British research in the 1960s showed that complete flower initiation of all shoots is obtained with 30 days of continuous lighting starting early February (5 mol m^{-2} d^{-1} natural light) and with 10 days in mid-April when the light sum is 15 mol m^{-2} d^{-1} or higher. The need for lighting varies widely among the current standard and spray carnation cultivars. Lighting is no longer necessary when the shoots have been initiated (Blacquière, 2000). To determine that moment, the meristem tissue is dissected. To advance flowering with approximately 7-10 days, photoperiodic lighting is provided with cyclic or continuous lighting. This is done in January/February to increase shipments in May and in August to be able to harvest at the end of the year or to increase winter shipments. In addition, lighting is also provided in September and October for crops to be harvested before April. Flower initiation is possible in January/February if the shoots have at least seven full-grown leaf pairs, while in August and March the shoots need five.

A light level of about 1 µmol m^{-2} s^{-1} is required, depending on the type of LD treatment. Continuous or cyclic lighting had the same effect if the same light sum is provided during the night and lighting goes on all night (Blacquière, 1999). Incandescent lamps are suitable for this purpose due to their far-red radiation component. In many other lamp types this is lacking. The LD effect depends on both the red and the far-red radiation. With continuous lighting, lighting is provided all night for 8-14 days. When the crop is uneven in development, this may be repeated after an interruption of 14 days. Cyclic lighting is applied for 3-6 weeks, for 7.5-10 minutes per half hour during four hours each the night. This method provides a slightly better quality (less elongation), less shoot reduction, and a better flower initiation in an uneven crop. During the summer, the production of a second year crop can be stimulated during periods with overcast weather by providing continuous lighting during 6-8 nights per month (DLV, 1998).



Standard and spray carnations are quantitative LD plants.
The critical daylength is 14 hours.
Short-day stimulates branching.
Under LD conditions, the shoot initiation is inhibited.
The crop has a very high light requirement. Light levels below 20 mol m^{-2} d^{-1} result in a reduced growth rate (T). Spray carnations have slightly higher demands with respect to light and temperature compared to standard carnations (Horn, 1996).

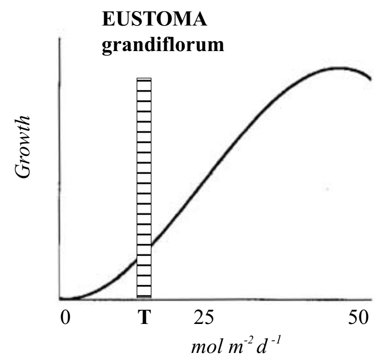
Eustoma grandiflorum or Lisianthus

This crop is native to Nebraska, Colorado, and Texas (US), lat. 32°-42°NL. For this reason, this plant is also referred to as Prairie Gentian or Texas Bluebell. Growers most frequently use the name Lisianthus russellianus. The name Eustoma was introduced earlier in 1806 (Hetterscheid, 1995). Lisianthus is a perennial but is also used for annual cropping. Best results are obtained at greenhouse temperatures between 15 and 25°C, while soil temperature should not drop below 15°C. The plant spacing is a function of the available light: above 700 µmol m^{-2} s^{-1} inside the greenhouse, plant spacing can be at a maximum density (June/July). This summer-flowering crop can be grown in The Netherlands during the fall and winter only with the help of supplemental lighting. Production times vary from 16 to 12 weeks for plantings in December-February and March-June, respectively. Seedling production takes two to three months. Seedling size has a large effect on production time and harvest period. The plants probably have a juvenile phase during which they are not sensitive to LD conditions. If the plants are larger than 3 to 4 cm, they are LD-sensitive (Blacquière, 1997b). To avoid uneven growth, sufficiently sized plants should be planted. During the production of young plants and seed formation, the temperature should not be too high, to avoid rosette formation. Manipulating the crop through photoperiod and temperature control is best carried out with the help of bud stage analysis.

Daylength

Eustoma is a quantitative LD plant, comparable to carnation. Growth, production period, and flower quality are affected by daylength and light intensity. The production time is reduced by LD conditions, high light levels, and high temperatures. But the latter may be at the expense of stem quality, length, and the number of leaves being differentiated (Blacquière, 1997b). Internode elongation increases with daylength, while the number of internodes below the first flower bud decreases. A photoperiod of 17 or 20 hours reduced the total number of leaf pairs compared to at a photoperiod of 10 or 14 hours (Blacquière, 1997b). The final stem length was about the same because of increased elongation of the internodes. At a 14-hour photoperiod, flower stems developed more leaf pairs under the first flower bud compared to at a 17-hour photoperiod. The number of flowers per stem, however, did not change. At a 17-hour photoperiod, the primary flowers were on lower nodes. The flower initiation took place sooner, and since flowers developed sooner, this led to an earlier harvest.

Based on what has been described above, the lighting period/photoperiod can be an important tool not only to influence the light sum affecting plant photosynthesis but also to control crop growth. For example, when a 14-hour daylength is maintained, stems get heavier because production time increases. Changing the daylength from 10 to 20 hours affects stem length but this is cultivar dependent. The production period is reduced inversely proportional with an increase in the photoperiod. Using a 17-hour photoperiod, production time is shortest, and longest at 10 hours (Blacquière, 1997a,b). The photoperiod effect is cultivar dependent. If during the first 80 days after planting a daylength of 10 hours was applied, and subsequently 17 hours, the heaviest and longest stems were obtained. The production period, however, increase compared to when during the entire cropping period a 14 or 17 hour daylength was applied (Blacquière, 1997a). Furthermore, it was observed that the production period could be shortened by an additional short period of far-red light. This light is present in incandescent lamps, but is lacking in high-pressure sodium lamps. Selecting the biggest plants from a seedling tray advanced the harvest and shortens the harvest period, but also resulted in weaker stems (Blacquière, 1997b). Application of supplemental lighting resulted in a reduction of flower bud abortion (resulting in fuller central branches) and more and bigger flowers. The shoots of the second flush showed a more vigorous growth, resulting in increased production.



Eustoma is a quantitative LD-plant. Flower initiation and development are accelerated under increased photoperiods of up to 20 hours. The critical photoperiod is cultivar dependent. For 'Kyoto Picotee Blue', it is 14 hours, for 'Fuji' 16 hours (Blacquière, 1997a).
Growth, production time, and flower quality are influenced by photoperiod and light intensity. The production time is reduced by LD conditions, high light intensity, and high temperatures. However, higher temperatures can have a negative effect on stem firmness, length, and number of leaves.
*The crop has a very high light requirement. The target (**T**) value for minimum acceptable quality and growth is 9 mol m^{-2} d^{-1}.*

Photoperiodic lighting

Photoperiodic lighting could also be used to advance flowering (Blacquière, 1997c). Eustoma is most sensitive to night interruption around the eighth hour after the beginning of the dark period. If continuous lighting was provided with incandescent lamps at 2 µmol m^{-2} s^{-1}, flowering occurred 18 days sooner compared to a crop grown under a 12-hour photoperiod. Under these conditions, total stem length was slightly shorter. Nevertheless, stem weight was about the same: 40 g for the cultivar 'Fuji Pink' and 45 g for 'Fuji White'. In California (35° NL.), with three to four times as much light as in The Netherlands (approximately 9 mol m^{-2} d^{-1}), photoperiodic lighting is sufficient to obtain high-quality flower stems. A 16-hour photoperiod is then applied. In The Netherlands (52° NL.) using only photoperiodic lighting is insufficient. Year-round production is possible with at least 50 µmol m^{-2} s^{-1} and a daylength of 18-20 hours (Nijentap, 1999).

Supplemental lighting

To avoid light stress under high light intensities such as 75 µmol m^{-2} s^{-1}, the photoperiod is gradually increased from 12 hours during the first five weeks of the production cycle, followed by 16 hours, and 18 hours during the last 10 weeks (Stijger, 1999). Depending on cultivar, a 24-hour photoperiod is possible (but commercially experience).

In The Netherlands, if supplemental lighting is provided for 20 hours at an intensity of 50 µmol m^{-2} s^{-1}, the light sum in the greenhouse is at most 5.9 mol m^{-2} d^{-1} (2.3 ambient + 3.6 supplemental). Under these conditions, the quality is average with respect to the number of buds, flowers per stem, and a keeping quality of at least 8-9 days. A negative aspect was that flower buds, which opened under living room conditions with less than 20 µmol m^{-2} s^{-1}, lost their color (Kabawata, 1995). In addition, white picotee flowers with purple or pink margins lost color at the margins. Pink and purple cultivars faded. Research results indicated that the fading of the flower color (anthocyanins) is caused by a lack of sugar (sucrose) due to the low rate of photosynthesis. Improvements in flower color can be achieved by adding sugar to the vase water, or by growing under sufficiently high light sums. No fading was observed during Japanese research when supplemental lighting was provided for 14 hour at an intensity of 175 µmol m^{-2} s^{-1}. This equals to a light sum of 8.8 mol m^{-2} d^{-1}. In view of results obtained in California, a target light sum for a good quality of 9 mol m^{-2} d^{-1} is recommended. In The Netherlands, a lighting intensity of at least 100 µmol m^{-2} s^{-1} is needed to achieve this. The wide range of cultivars offers increasing possibilities to select special cultivars suitable for a particular season. There are cultivars that can be grown at low light levels and SD treatments ('Ventura'), but other cultivars give the best results under high light and LD treatments ('Mariachi', 'Flamingo' or 'Kyoto'). Moderate light and daylength conditions are required by the cultivars 'Heidi', 'Fuji', 'Malibu', 'Candy', and 'Echo'.

Freesia hybrids

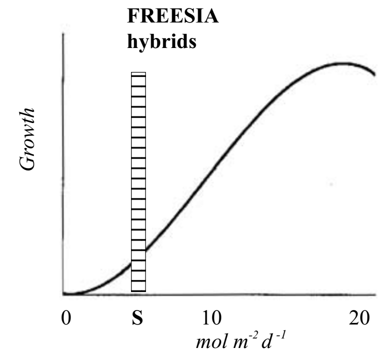
Advantages of supplemental lighting

The quality and the production of flower stems as well as the quality of the new corms are improved by supplemental lighting. Main stems and laterals grow bigger rachis with more flower buds/spikes. Harvest of the main stems is considerably advanced (by four weeks), as well as by two weeks for the laterals. The harvest peak during spring is reduced resulting in a more constant labor requirement throughout the year.

Growing conditions

In its native country, South Africa (30-35° SL.), there is more natural light compared to in The Netherlands. Natural growth in South Africa occurs during the winter season, when light sums, estimated at 11 to 18 mol m^{-2} d^{-1}, are 3 to 5 times higher compared to in The Netherlands. In Dutch greenhouses, the average light sum decreases from about 16 mol m^{-2} d^{-1} at the beginning of September to 2.3 mol m^{-2} d^{-1} in December. It is obvious that there is a significant light deficit during winter production.

Light shading, partly to keep the greenhouse cool, was activated when the outside global radiation reached values of 250-450 W m^{-2} (DLV, 1997). In March, the lower value can be used in order to get the plants accustomed to the strongly increasing transpiration and light intensity. Towards the summer the value is



Although freesia is basically DN, it does respond to different photoperiods. The initiation of leaves is stimulated by LD conditions (vegetative growth), while the flower initiation is accelerated by SD conditions (8-10 hours).
LD conditions promote the formation of new corms and cormlets.
The formation of laterals is stimulated by SD conditions, as well as the flower bud initiation and stem quality. LD conditions (up to 14 hours) shorten the period until flowering after flower initiation.
The minimum target light sum for good production is 4 mol m^{-2} d^{-1}. The crop has an average light requirement.

gradually increased, together with the light sum. The light sums during April correspond closely to those in South Africa (on average 17 mol m^{-2} d^{-1}).

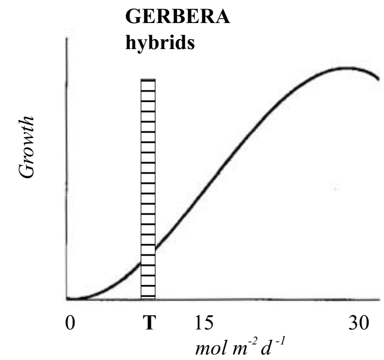
The use of supplemental lighting can reduce the light deficit during the winter months, although another option is to use wider plant spacing and lower temperatures. However, in the latter case, the production period is increased. Normally, during flower stem production, the greenhouse temperature during winter is relatively low (8-10°C).

Lower production temperatures can quickly lead to a surplus of heat when a co-generation installation is used for the generation of electricity. This can severely limit the application of supplemental lighting for freesia. As a possible solution, the temperature can be slightly increased in relationship to the higher light environment and carbon dioxide enrichment.

Lighting

Experiments at Wageningen University and the Research Station in Naaldwijk (The Netherlands) demonstrated that optimizing the supplemental lighting based on achieving certain light sums could offer tremendous benefits. A light intensity of 35 µmol m^{-2} s^{-1} was desirable, while the lighting period depended on the desired light sum (Berghoef, 1991). The minimum target value was set at 4 mol m^{-2} d^{-1}. This light sum is achieved inside a greenhouse around the beginning of February and the end of October in The Netherlands. In December, this light sum is only 2.3 mol m^{-2} d^{-1}. A supplemental light sum of 4.0 - 2.3 = 1.7

mol m^{-2} d^{-1} is therefore needed in December.
At a light intensity of 35 µmol m^{-2} s^{-1}, this means almost 14 hours of supplemental lighting. As a result of this lighting strategy, the fresh and dry mass of the main stem and laterals increased with 50% or more. In addition, stem length increased (10%). The number of healthy buds per inflorescence on the main stem increased with 40%. The dry mass of the new corms was tripled. Commercially, HPS lamps are used to provide a photoperiod of 16-20 hours and a light intensity of 35 µmol m^{-2} s^{-1} with a minimum dark period of 4 hours.
For the formation of new corms and cormlets, LD conditions have a positive effect. As the daylength increases, the assimilates from photosynthesis are transported more towards the subterranean than to the aerial parts of the plant. This can be at the expense of the quality of the main stem, and especially that of the laterals. This change in the distribution of assimilates takes place under a daylength ranging from 16-20 hours. The formation of laterals, and the flower bud initiation and corresponding stem quality are improved by SD conditions. LD conditions can shorten the production time by two weeks. Based on research, for flower production, lighting would only make sense when the main stem is 15-20 cm long. When lighting was started at an earlier stage, the extra assimilates went to the new corm and not to the laterals. Thus, the second lateral was not or not enough initiated. The latter did not start growing before the main stem was longer than 20 cm. Lighting at that point had a favorable effect on quality. Experiments indicated that lighting during the first phase after planting may have a favorable effect on the final result. If the light sum during this phase is too low, the final quality will be poorer. A 20-hour photoperiod during this phase was unfavorable (Doorduin, 1999). When lighting was applied after emergence, a 14-hour photoperiod was recommended until the flower stem reached a length of 20 cm (Van der Hoek, 1998). If only the main stem was harvested, lighting can be stopped two weeks before flowering without loss of quality. However, if in addition the growth of the new corm and cormlets had to be stimulated, lighting was continued until the middle of the harvest period. If during the winter, high quality corms and cormlets have to be harvested, supplemental lighting is necessary. The minimum light intensity appears to be 35 µmol m^{-2} s^{-1}, higher levels would be preferred, especially considering the conditions in South Africa as well as more recent research results (Doorduin, 1999). In The Netherlands, during December, the minimum light sum is not achieved on many days. It is recommended to increase the light intensity from 35 to 50 µmol m^{-2} s^{-1}. The data from Norway confirm this, where lighting was applied for 20 hours with intensities of 80, 130 and 180 µmol m^{-2} s^{-1}. The highest light intensity shortened the production period by only a few days. The corm mass increased linearly with the light intensity applied (Gartner Yrket, 6/1997). Higher light intensities hardly affected the keeping quality. More light towards the end of the crop cycle leads to improved quality. These conclusions correspond with Dutch research data. The conclusion is that a light intensity of 80 µmol m^{-2} s^{-1} is sufficient. This corresponds with a target light sum of up to 6 mol m^{-2} d^{-1}. In current growing practices in The Netherlands, an average of three months of supplemental lighting is applied on an overall growing period of 6-7 months. Therefore, approximately half the growing area receives supplemental lighting at any given time. By using movable fixtures, a lighting capacity for 50% of the total production area is sufficient. Some commercial operations provide a relatively low light intensity of 25 µmol m^{-2} s^{-1} over the entire production area, and use additional movable fixtures, to be able to provide extra lighting during certain production stages.



Gerbera is a quantitative SD plant.
The critical daylength is 14 hours.
SD conditions improve branching and flower initiation. LD conditions and high temperatures during the summer inhibit branching of rhizomes and flower bud initiation. Gerbera is only slightly photoperiodic but dramatically respond to the light sum (Rogers and Tjia, 1990).
*The outgrowth of flowers is stimulated by high light sums. For pot gerbera, a daylength of 20 hours and a high light level (up to 70 µmol m^{-2} s^{-1}) during the winter increased the number of sideshoots and quadruplicated the number of flowers. This crop has a high light requirement. The minimum target value (**T**) for flowering and development is between 6 and 8 mol m^{-2} d^{-1}.*

Gerbera hybrids

This crop is native to Natal and Transvaal in South Africa (25-30° SL). It has a high light requirement, which is manifested in its seasonal production in The Netherlands: low during the winter and high during spring. Lighting from the beginning of March to June can improve quality and production. Even during that period of the year, the crop does not experience light saturation. Gerbera is only slightly photoperiodic but dramatically respond to the light sum (Rogers and Tjia, 1990).

Flower initiation

The flower initiation is promoted by SD conditions, when the photoperiod is less than 14 hours. By contrast, flower development strongly depends on high light sums, through LD conditions and high light intensities. During December, more flower buds are initiated in unlit compared to in lit crops. But most flower buds of unlit plants only develop when light conditions improve. Thus, the plants accumulate flower buds. LD conditions and high temperatures during the summer inhibit branching of the rhizomes as well as flower bud initiation. Without additional lighting during the winter, production drops sharply. The flower stems become thinner and the flowers are smaller. This situation can be significantly improved by using supplemental lighting. The longer the lighting period and the higher the light intensity, the larger the improvement. There appears to be a relationship between light intensity and photoperiod. Research by Leffring (1981) demonstrated that a daylength of 8 to 10 hours is optimal. SD conditions (8 hours) resulted in a higher flower initiation compared to LD conditions (16 hours). This is due to the fact that under SD conditions:

- The main shoot of the rhizome flowers the earliest and continues to grow;
- The highest number of lateral shoots is formed, which also continue to grow.

The flower production is highest under SD conditions, as a result of these responses of the main and side shoots. High light intensities, but also low temperatures stimulate the SD responses.

Lighting

The optimum lighting period depends on the light level. The SD responses appear to occur to a certain extent also under LD conditions, provided the light level is sufficiently high. At a light intensity of 50 μmol m^{-2} s^{-1}, the minimum photoperiod is 16 hours (20 hours perhaps slightly better), at 28 μmol m^{-2} s^{-1} a 12-hour photoperiod is optimal (a longer photoperiod does not result in additional responses). A light intensity of 18 μmol m^{-2} s^{-1} provided no response, not even when the photoperiod was extended to 20 hours. Apparently, this intensity is below the threshold value. If the intensity is too low, no responses were observed (Van Os, 1988/1989). During these experiments, supplemental lighting was provided only during the night (*e.g.* in December for a 12-hour period).

Lighting with an intensity of 50 μmol m^{-2} s^{-1} increased winter production by 50% during the period from October to March, but it also caused a reduce production from March to May. This relapse could be limited if continued lighting after late February was provided with sufficient intensity. Through May, the reduction in production was only 9% when using a light intensity of 50 μmol m^{-2} s^{-1} and 22% at an intensity of 28 μmol m^{-2} s^{-1}. The overall production from October through May was 15% higher at 50 μmol m^{-2} s^{-1} compared to the control treatment.

The reduction in production after February does not have to be a serious drawback. During that period, the regular supply increases strongly, resulting in decreasing prices. The economic benefits should come from the additional production during the period prior to that. In addition, the shift of production towards the winter months results in a more constant labor requirement.

Other effects were: almost 2°C higher leaf temperatures at a light intensity of 50 μmol m^{-2} s^{-1}, a higher number of flower buds (a 19% increase using a light intensity of 50 μmol m^{-2} s^{-1} compared to a control treatment from October through February), reduced flower bud abortion or bud drop during winter, faster development from flower bud initiation to harvest (reductions of half a week in October to two weeks for flower buds initiated in January, which normally take seven weeks to grow, now only five weeks), and longer and thicker flower stems with bigger flowers and more intense flower color. The flower mass was increased by more than 50% during the winter months using a light intensity of 50 μmol m^{-2} s^{-1} compared to a control treatment. Even in April, the effect was significant. During this month, lighting adds a mere 14% to the total light sum, but flowers were 25% heavier when compared to the control plants. When lighting was stopped on the first of March, flower mass dropped rather rapidly to the flower mass of the control treatment. The percentage of dry matter increased resulting in an increased firmness. After transportation and dry storage, a lit gerbera recovered better and dries out less quickly compared to an unlit flower. After harvest, a lit stem elongates more compared to an unlit stem, but this has no effect on possible stem bending. A side effect of lighting is that the leaves are tougher and darker in color.

Recommendation

Practical experience showed that a movable lighting installation with three 600 W lamps, moving at speeds of 20 to 60 m per hour, were not quite satisfactory (Bouwman, 1999). Optimum lighting conditions requires a light intensity of at least 50 μmol m^{-2} s^{-1}, or even twice as high. Supplemental lighting during the daytime appears feasible. The length of the photoperiod remains a point of debate. Recent experiments involving commercial greenhouse operations showed that a 14-hour photoperiod and a light intensity of 50-70 μmol m^{-2} s^{-1} are recommended. A16-hour photoperiod seemed to be the maximum using those intensities.

Installed lamp capacity and resulting light intensity.

Source: Maaswinkel, 1996.

*For **high-pressure sodium** (SON-T Plus 400 W) light:*

1 μmol $m^{-2}s^{-1}$ = 85 lux = 0.2 Wm^{-2} PAR = 7.9 ft-c

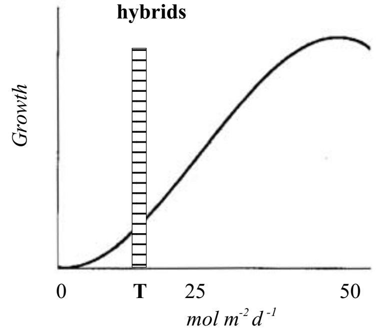
1 lamp for every 18 m^2 of floor area results in:

5.8	$W m^{-2}$ (PAR) or
29	μmol m^{-2} s^{-1} or
2,465	lux or
229	ft-c

1 lamp for every 9 m^2 of floor area results in:

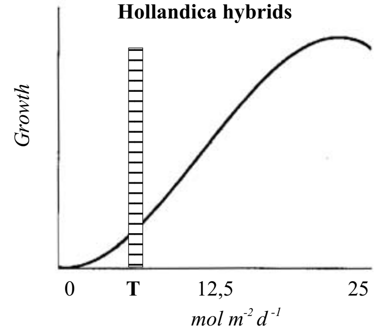
11.6	$W m^{-2}$ (PAR) or
58	μmol m^{-2} s^{-1} or
4,930	lux
458	ft-c

GLADIOLUS hybrids



*Gladiolus is DN for flower initiation but is a facultative LD plant for flower development. Under LD conditions more assimilates are directed to the flowers than to the tuber. This enhances the number of flowers. The crop has a very high light requirement. The threshold (**T**) value for flower initiation is 13 mol m^{-2} d^{-1}.*

IRIS Hollandica hybrids



Iris responds to LD conditions.
Daylength extension to 16 hours improves flowering.
*The threshold value (**T**) for flower initiation is at approximately 5 mol m^{-2} d^{-1}.*
The light requirement is high.

Gladiolus hybrids

This plant, which is grown from a corm, is sensitive to supplemental and photoperiodic lighting. The threshold value for flower initiation is reported to be 13 mol m^{-2} d^{-1} (Gude, 1998). This corresponds with approximately 1,000 J cm^{-2} d^{-1} of outside global radiation. In The Netherlands during the period from early September through the beginning of April, the light sum in the greenhouse does not reach this level. For gladiolus, the sensitivity to the amount of light deficiency depends on the development stage. The 4-6 leaf stage is most sensitive. Light deficiency during that stage leads to a smaller percentage of flowering and fewer flowers per spike. Light deficiency after the sixth leaf stage does not affect the percentage of flowering, but the number of flowers per spike is reduced. To grow gladioli during the winter in The Netherlands, supplemental lighting should be provided with high light sums. For instance, during October an additional 6.1 mol m^{-2} d^{-1} is needed, requiring 20 hours of lighting at an intensity of 85 μmol m^{-2} s^{-1}.
Flowering can be improved under low light conditions using photoperiodic lighting. This is done from the third to fourth leaf stage onwards. The daylength is extended with incandescent lamps to at least 16 hours (from 18:00 to 22:00 hr or from 22:00 to 02:00 hr) with a light intensity of 1-4 μmol m^{-2} s^{-1}. This results in a higher percentage of flowering, a longer stem, and more flowers per spike. The disadvantage is an increase in production period.

Installed wattage of incandescent lamps (150 W) and resulting light intensities at 2 m below the lamps. Source: PBGA, 1996.

Light intensity (average) *μmol m^{-2} s^{-1}*	***Installed lamp wattage watt per 10 m^2***	***Number of lamps per 10 m^2 of floor area***
1.5-2.0 (1.75)	*15*	*1*

To obtain the same light intensities using 18 W compact fluorescent lamps, four times as many, and using 18 W fluorescent and low-pressure sodium lamps, three times as many lamps must be installed.

Hyacinthus orientalis

Hyacinthus, Tulipa and Narcissus do not require supplemental light for flowering. They do require photoperiodic light, which stimulates a good color and flower development (see the section on Tulipa).

Iris Hollandica hybrids

The threshold light sum for flower initiation is 5 mol m^{-2} d^{-1}. Providing a lower light sum results in bud abortion. A photoperiod of 16 hours improves the flowering. Compared to Asiatic hybrid lilies, the threshold light sum for Iris is somewhat lower, but higher than for Lilium longiflorum and Oriental hybrids (Gude, 1988). The threshold light sum implies that, in The Netherlands during December, the natural light sum in the greenhouse should be doubled. To achieve this, a minimum PPF of 32 μmol m^{-2} s^{-1} should be provided during a photoperiod of approximately 20 hours.

Converting instantaneous light levels and light sums

*For **high-pressure sodium** (SON-T Plus 400 W) light:*
1 μmol $m^{-2}s^{-1}$ = 85 lux = 0.2 Wm^{-2} PAR = 7.9 ft-c (1)

For the conversion of lux to footcandle: 1 ft-c = 10.76 lux
For lux and ft-c as basis, the conversions are:
1,000 lux = 11.8 μmol m^{-2} s^{-1} = 2.4 W m^{-2} PAR = 92.9 ft-c
1,000 ft-c = 126.6 μmol m^{-2} s^{-1} = 25.3 W m^{-2} PAR = 10.76 klux

Measurements by the Research Station for Floriculture and Glasshouse Vegetables in Aalsmeer, show variations from 11.9 to 13.4 μmol m^{-2} s^{-1} per 1 klux.
The number of μmol m^{-2} s^{-1} per klux increases as the lamps get older and the lamp voltage is increased.

*For **daylight**, the following conversion can be used:*
1 μmol $m^{-2}s^{-1}$ = 56 lux = 0.217 Wm^{-2} PAR = 5.2 ft-c (2)
For lux and ft-c as basis, the conversions are:
1,000 lux = 17.9 μmol m^{-2} s^{-1} = 3.9 W m^{-2} PAR = 92.9 ft-c
1,000 ft-c = 192.3 μmol m^{-2} s^{-1} = 41.8 W m^{-2} PAR = 10.76 klux
The type of weather plays an important part in this conversion, see Table 5.2

Light sum using HPS
*1 MJ m^{-2} PAR = 5 mol m^{-2} = 118 klxh = 10,970 ft-ch **(3)***

***Daylight sum** (45% PAR of total radiation)*
*1 MJ m^{-2} PAR = 4.6 mol m^{-2} = 71.9 klxh = 6,640 ft-ch **(4)***

Lilium

Assortment of cultivars

The current range of cultivars mainly originates from wild species native to China and Japan. In The Netherlands, five groups of cultivars are important:

1. **Oriental hybrids** derived from species such as Lilium speciosum, L. auratum and L. rubellum; examples: 'Star Gazer', 'Siberia', 'Casa Blanca', 'Acapulco', 'Le Rêve'.
2. **Asiatic hybrids** derived from many different species (12) and consisting of many cultivars such as 'Pollyanna', 'Vivaldi', 'Elite'. These also include the Mid-Century hybrids such as 'Enchantment' and 'Tabasco'.
3. **Longiflorum hybrids** such as 'Snow Queen', 'White Fox'. Easter lilies belong to this group as well.
4. **L/A hybrids** derived from crosses between groups 2 and 3, including 'Royal Fantasy', 'Donau', and 'Salmon Classic'.
5. **Speciosum.**

The first two groups are by far the most important, group 3 and particularly group 4 are growing strongly. Group 5 will probably disappear. In 1996 a new group of O/A hybrids developed by crossing between 1 and 2.

For winter production, supplemental and photoperiodic lighting is usually needed. Photoperiodic lighting can be used to reduce the production period for some cultivars belonging to the Oriental hybrids and to the Speciosum group. A minimum daylength of 16 hours is required.

Disorders

SD conditions, low light intensities, and high temperatures may result in a loss of flower buds in sensitive cultivars. This may be caused by:

1. Abortion

of flower buds on third order laterals, which do not develop beyond the stage of small tips in the axils of bracts (Roh, 1990);

2. Bud blast

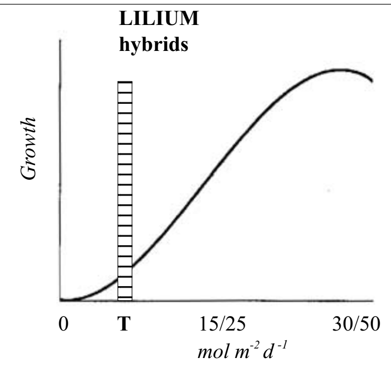
in well-developed flower buds up to 2 cm in diameter at the top of the inflorescence. At their base these buds become brown and may eventually drop off the pedicel during forcing in the greenhouse, but they rarely do after harvest (Roh, 1990). In fact, bud blast can be defined as bud abortion, although the latter term is used for bud death at a very early stage.

Bud blast

Asiatic hybrids are sensitive to bud blast, such as 'Connecticut King', 'Dream Land', 'Pollyanna' and 'Medaillon'.

Bud drop

Asiatic hybrids are sensitive to bud drop with distinct variations between the cultivars, 'Enchantment' being very sensitive. Oriental hybrids and Longiflorum are less sensitive, while Speciosum is virtually insensitive.



Lilium Oriental hybrids and Speciosum are sensitive to LD conditions. Using photoperiod lighting, the flowering can be advanced. A 16-hours photoperiod should be applied.

*If the light sum remains below a threshold value (**T**), bud blast and/or bud drop develop. The threshold values are:*

1. *Asiatic hybrids:* 5.3 mol m^{-2} d^{-1}
2. *Oriental hybrids:* 4.1 mol m^{-2} d^{-1}
3. *Longiflorum:* 3.7 mol m^{-2} d^{-1}

The light requirement is high (3) to very high (1, 2).

The Bulb Research Centre in Lisse, The Netherlands, uses the unit Wh m^{-2} d^{-1} *to represent these threshold values:*

Asiatic hybr.: 320 Wh m^{-2} d^{-1} PAR or 115 J cm^{-2} d^{-1} PAR
Oriental hybr.: 250 Wh m^{-2} d^{-1} PAR or 90 J cm^{-2} d^{-1} PAR
Longiflorum : 225 Wh m^{-2} d^{-1} PAR or 81 J cm^{-2} d^{-1} PAR

For example, if the desired light sum is 320 Wh m^{-2} d^{-1} *and the light sum in the greenhouse in mid-December is 144* Wh m^{-2} d^{-1}*, a deficiency exists of 176* Wh m^{-2} d^{-1} *(Gude, 1998).*

Supplemental lighting with a light intensity of 8 W m^{-2} PAR *and a 22-hour photoperiod can compensate for this light deficit.*

3. Bud drop (abscission)

This usually occurs in flower buds of the second and third order (2-3.5 cm in diameter). It starts at the bottom of the inflorescence and spreads upwards. The bottom flowers have developed further than the top ones. The flower base shrivels and subsequently gets a paperlike quality. At the bud attachment to the pedicel, an abscission layer develops causing the bud to drop off. The flower buds are at a stage in which pollen are formed (Kamerbeek, 1971). At that stage the flowers are sensitive to ethylene, which is involved in bud drop. Under stress conditions, such as low light levels, the production of this hormone increases (Van Meeteren, 1982). In addition, there is a likely shortage of sugars (especially sucrose). This condition causes stress during the rapid growth phase when sugars are absolutely necessary (Roh, 1990).

Although bud blast and bud drop have much in common, they are not the same (Durieux, 1982/83). Bud blast is less sensitive to ethylene than bud drop.

Bud drop will become more likely when the days get shorter. This phenomenon is also affected by the cooling period (vernalization) of the bulbs before planting (Kamerbeek, 1971). Bud blast can be induced by ethylene and low light at all stages of development, while bud drop only during the critical stage (Roh, 1990). During postharvest, bud drop may occur at all stages of development, such as dark storage and high temperatures. Such conditions strongly stimulate the respiration and the growth rate of the shoot, leading to competition for sugars between leaves and stem on the one hand and the developing flower buds on the other. When the production of sugars is limited, the flower buds are aborted (Roh, 1990). Orientals hybrids are not sensitive to this.
Other typical winter problems are:
Elongated, weak stems with long internodes and pedicels, and poor flower quality with pale colors.

Light sensitivity
The sensitivity for light varies widely among the different groups and cultivars. The sensitivity is based on minimum quality requirements and incidence of bud blast and bud drop. Generally, Oriental hybrids are the least sensitive, while Asiatic and L/A hybrids the most sensitive, and L. longiflorum falls somewhere in between. Examples of minimum threshold light sums are:

- Asiatic hybrids: 5.3 mol m^{-2} d^{-1}
- Oriental hybrids: 4.1 mol m^{-2} d^{-1}
- Longiflorum: 3.7 mol m^{-2} d^{-1}

Light saturation
For the pot lily, Lilium longiflorum ‘Nellie White’, it was observed that leaf photosynthesis (fifth leaf from the top) was saturated at 700 µmol m^{-2} s^{-1} (100%) while at 200 µmol m^{-2} s^{-1} it was 85%. At lower intensities, photosynthesis decreased sharply: only 28% at 100 µmol m^{-2} s^{-1} (Wang, 1990).
If these levels are compared with the natural light conditions in a greenhouse, it is obvious that during the winter the rate of photosynthetic is well below saturation. The average daily light intensity in a Dutch greenhouse is, for the months from October through February: 200, 115, 85, 100 and 170 µmol m^{-2} s^{-1}, respectively. However, growth not only depends on the rate of leaf photosynthesis. It also depends on the light sum. Suppose that a minimum daily light sum of 3.7 mol m^{-2} d^{-1} is required. If (for Dutch conditions) during December the average natural light sum is 2.3 mol m^{-2} d^{-1}, then 1.4 mol m^{-2} d^{-1} has to be added through supplemental lighting. This can be achieved by providing supplemental lighting for 13 hours and a light intensity of 30 µmol m^{-2} s^{-1}.

Effects of lighting
Supplemental lighting improves plant quality and permits higher plant densities. In the past, plants were spaced at twice the distance during the winter compared to the summer. Economically, this is no longer justified. In general, supplemental lighting reduces stem length, improves stem sturdiness, leaf color, and keeping quality, while reducing the production period. The effects, however, vary with hybrid group and with cultivar within a group. Stem length is reduced the most for Asiatic hybrids, while the production period is reduced the most for the Oriental hybrids.
Generally, Oriental hybrids have a longer production period (100-120 days) compared to Asiatic hybrids (70-80 days). Partly as a result of increased competition, supplemental lighting is required for year-round cropping. By using movable luminaries that travel along special rails supplemental lighting can be used for several crops. This increases the economic benefits of using supplemental lighting.

Lighting period
The length of the lighting period during production increases continuously. In the past, supplemental lighting was applied during the last four to five weeks of the total cropping cycle of 10-12 weeks. Currently, this has increased to six to seven weeks. For the bud drop sensitive Asiatic hybrids, lighting is started as soon as the flower buds are visible (about 1 cm long), or sometimes even at emergence (*e.g.* ‘Connecticut King’). This practice would also benefit the development of the flower buds, since research with Asiatic miniature hybrids pointed out that the flower buds are initiated already in the bulb (Zhang, 1990). The number of flowers depends on bulb age and, consequently, on bulb size.
Lighting Asiatic hybrids and L/A hybrids starts around the first of October and continues through the end of March. Other less light sensitive hybrids are lit from early December through mid-January (L. longiflorum from a height of 20 cm onwards). In order to improve the overall quality, it is recommended to further extend the above stated length of the lighting period. Lighting prevents the stems from becoming tall and weak, while it improves flower bud quality.
Although L. longiflorum is less sensitive to bud drop or bud blast, these disorders may occur under very low light conditions. Using supplemental lighting on ‘Snow White’, the percentage of blind stems declined and stem quality improved (heavier and sturdier) (Brooymans, 1994). Lighting before the shoots reach a length of 20 cm directly affected flower initiation, which started already when stem length was between 10 and 15 cm (Pfeiffer, 1935).
Lilium speciosum ‘Uchida’ is not sensitive to bud drop during the winter, but supplemental lighting is needed to improve leaf, flower, and stem quality.

Photoperiod
The photoperiod can be extended to 24 hours using supplemental lighting for Asiatic, Longiflorum, and L/A hybrids, but this is not advisable for the Oriental hybrids. When photoperiods of 16-18 hours or more were provided to Oriental hybrids, the incidence of leaf necrosis and/or leaf spot (parchment-like withering of the leaves) towards the end of the produc-

tion period increased (Schouten, 1998). It is recommended not to exceed a 16-18 hour photoperiod, as was confirmed with the cultivars 'Star Gazer' and 'Acapulco' (DLV, 1998). For other sensitive cultivars, such as 'Le Rêve', 'Coulance', 'Journey's End', 'Happy Hour' and 'Stella Polare', a 16-hour photoperiod was considered the maximum (DLV, 1994).

Using the cultivars 'Enchantment' and 'Apeldoorn', it has been demonstrated that bud drop decreased with increasing photoperiods from 8 to 24 hours. For these experiments, the light sum for each photoperiod was kept the same by using lower light intensities. A 20-hour photoperiod is considered the minimum for the bud drop sensitive cultivar 'Enchantment'. For the less sensitive cultivar 'Apeldoorn' it is probably lower (Gude, 1988).

Lamp types

The use of HQI-T lamps (mercury metal halide) containing more blue light in their spectrum is being tested at the Bulb Research Center in Lisse, The Netherlands (Schouten, 1998). To date, for Oriental lilies, HQI-T lamps are not a real alternative for the HPS lamps, which are less, expensive, have a longer life, and are more efficient. Although HQI-T lamps emit a pleasant working light, represent the bud color well at harvest, and reduce the forcing period, these advantages do not outweigh the drawbacks, such as weaker stems, smaller buds, and many leaf spots. The leaf spots were not observed in subsequent trials. Reducing the greenhouse temperature by 1-2°C improves the stem quality, but delays flowering (Anon., 1998).

Light intensity

In The Netherlands in recent years, the recommended lighting intensity has increased to 55 μmol m^{-2} s^{-1}. For Oriental hybrids, a level of 40-50 μmol m^{-2} s^{-1} is frequently used in order to reach the minimum light sum requirements.

Photoperiodic lighting

Photoperiodic lighting is used to reduce the production period for winter plantings of Oriental hybrids (late December/early January). Reduction in the production time is highly cultivar dependent and ranges from several days to a few weeks. The flower bud development is accelerated when the daylength is extended to 16 hours during the six weeks after emergence. Flower buds have already been initiated in the bulb after the cold treatment. Due to quality loss, this lighting strategy cannot be applied during the fall. Incandescent lamps (one 150-watt lamp per 7.5-9.6 m^2 floor area) or compact fluorescent lamps are used for daylength extension. Reduction of the production period is somewhat less when cyclic (10 minutes during each half hour) instead of continuous lighting is used. A drawback of the energy efficient and durable compact fluorescent lamps is that they are less effective than incandescent lamps with respect to the reduction in production time. Photoperiodic lighting was performed with one 150-watt incandescent lamp or one 18-watt compact fluorescent lamp per 10 m^2 of floor area to provide similar light intensities (Philips NV). However, according to measurements performed at the Dutch Research Station (see below), the installed lamp capacity using the compact fluorescent lamps would have to be increased. The resulting difference in light intensity should be taken into account when assessing the results of the experiment.

For Oriental hybrids, lighting was provided from emergence onwards between 24:00 and 08:00 hr for a 16-17 hour photoperiod. The production period (143 days) of the cultivar 'Star Gazer' was reduced by 18 days under incandescent lamps and 10 days under compact fluorescent lamps.

For the cultivar 'Furore', the production period (135 days) decreased by 17 and 8 days, respectively.

For the cultivar 'Casa Blanca' (144 days), the reduction was 17 and 5 days, respectively.

The response of the cultivar 'Le Rêve' (109 days) to daylength extension was negligible: 3 days and 1 day, respectively.

The above is also valid for L. speciosum. 'Uchida' planted in January or March, showed a reduction of the production period, due to daylength extension from 23 to 20 and from 21 to 18 weeks, respectively. In this case, incandescent lamps and an installed capacity of approximately 20 W m^{-2} are required.

Narcissus, see Tulipa

Installed wattage of incandescent lamps (150 W) and resulting light intensities at 2 m below the lamps. Source: PBGA, 1996.

Light intensity (average) *μmol m^{-2} s^{-1}*	***Installed lamp wattage watt per 10 m^2***	***Number of lamps per 10 m^2 of floor area***
1.5-2.0 (1.75)	*15*	*1*

To obtain the same light intensities using 18 W compact fluorescent lamps, four times as many, and using 18 W fluorescent and low-pressure sodium lamps, three times as many lamps must be installed.

Rosa hybrids

Challenges

During the winter months, production and quality strongly decline, while blindness in many cultivars significantly increases. This crop has a very high light requirement and can only be grown properly year-round with supplemental lighting.

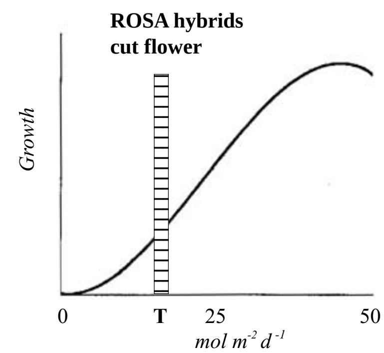
Background

Rose is DN with respect to flower initiation. Axillary buds do not yet have flowers initiated. The flower buds are initiated in the apical meristem of the laterals after sprouting of the axillary buds. If the light sum during sprouting is too low, the flower buds abort, resulting in 'blind' shoots, a common phenomenon during the winter. A small percentage of blindness is not a significant problem using the current cultivation methods. These methods promote the creation of an actively photosynthesizing leaf area. The old production method with upright high bushes, maintaining a constant leaf mass at the top, has changed. Currently, the bushes have short scaffold branches, or no scaffold branches at all if the arched pruning method is maintained. The flower stems are harvested at the knuckle, without leaving leaves on the bush as was common in the past. Using the bending system, a certain amount of healthy leaf area is maintained. Therefore, as many blind and low-quality flowering stems as possible are bent over (arching).

The growth of the shoots is stimulated by increasing the daylength (during spring), increasing light intensities, and higher temperatures. As a result, peak production is during the summer.

Sprouting of axillary buds

The sprouting of axillary buds is stimulated by a high red/far-red ratios (Tsujita, 1982; Mor, 1984. Roberts, 1993; Bakker, 1997b). Far-red light inhibits sprouting. HPS lamps with a high red/far-red ratio consequently promote sprouting, just like the supply of photosynthates to the growing shoots (Mor, 1980/1981). As a result, supplemental lighting stimulates the development of growing shoots (Bakker, 1997; Bredmose, 1997). The percentage of blind shoots is reduced when lighting is done with increasing light intensities, especially during flower initiation which occurs shortly after sprouting of axillary buds (Bredmose, 1997b; Maas, 1995).



Rose is DN.
*Flowering is stimulated by high light sums. The minimum threshold (**T**) light sum for good quality and production is approximately 12-13 mol m^{-2} d^{-1}.*
Increasing the light sum from 18 to 21 mol m^{-2} d^{-1} could reduce the percentage of blind shoots for several cultivars by 50% (Bredmose, 1997).
The light requirement is very high.

Photoperiod and light sum

Production increased linearly with supplemental lighting (Bredmose, 1997a). The photoperiod influenced the distribution (sink/source) of photosynthates.

At a given light sum, the production sometimes improved using a 17-hour photoperiod compared to a 20-hour photoperiod (De Hoog, 1994; Bakker, 1996). But the reverse was also observed. Furthermore, a 12-hour photoperiod could be as effective as 24 hours at half the light intensity, while other experiments demonstrated that when using an equal light sum, a 24-hour photoperiod gave much better results (Jiao, 1991). The appropriate photoperiod/lighting period combination has to be found for each cultivar to get the biggest benefit from the use of supplemental lighting. For the cultivar 'Madelon', the number and total mass of the basal shoots was the largest using a 17-hour daylength, for 'Frisco' 17 or 20 hours are better than 14 hours. The development of basal shoots was fastest for the cultivar 'Frisco' after bending using a 14-hour daylength (De Hoog, 1994). The daylength occasionally also influences the size of the upper three-leaflet leaf or the leaves at the top of the flower stem. Using supplemental lighting to extend the daylength up to 17 or 20 hours, the upper three-leaflet leaf of the cultivar 'Madelon' gets bigger compared to using a daylength of 14 hours. This effect has also been observed with the upper five-leaflet leaf of the cultivars 'Frisco' and 'Gabriella' using a 20-hour daylength (Bredmose, 1997a). Furthermore, the number of petals increased linearly with a light intensity of up to 100 µmol m^{-2} s^{-1}.

Light requirements

For optimal production, roses have a very high light requirement (30 mol m^{-2} d^{-1} or higher). In European greenhouses, these levels do not occur. The outdoor average light sum varies during the summer from 40 to 50 mol m^{-2} d^{-1} (Wallen, 1970). Consequently, crop photosynthesis and production can therefore be further increased during the summer. Experiments in Norway demonstrated this (Gislerød, 1997). Supplemental lighting was provided with an intensity of 210 µmol m^{-2} s^{-1} and a 20-hour photoperiod, as soon as the light level inside the greenhouse dropped below 300 µmol m^{-2} s^{-1}. This increased the yield of the cultivars 'Kiss' and 'Baronesse' by 40-50%, which was close to the increase in light sum (40%). However, if insufficient additional carbon dioxide is supplied (800-1,000 ppm), a large part of the potential increase in yield is lost. In similar experiments, light sums of 25

Light intensities and photosynthesis in rose

Single leaf photosynthesis saturates at approximately 500 µmol m^{-2} s^{-1}.
Whole crop photosynthesis saturates at 1,000 µmol m^{-2} s^{-1} during the summer, and 750 µmol m^{-2} s^{-1} during the winter (Jiao, 1991).

In The Netherlands, the average light intensity inside the greenhouse does not exceed:
750 µmol m^{-2} s^{-1} in June, and
175 µmol m^{-2} s^{-1} in December/January.
See also Table 5.4.

to 30 mol m^{-2} d^{-1} were provided using light intensities of 350 to 420 µmol m^{-2} s^{-1} for 20 hours. Even under these conditions, crop photosynthesis did not reach saturation. Saturation occurred at light intensities above 1,000 µmol m^{-2} s^{-1} (Jiao, 1991; Baille, 1996), and according to French experiments not until 1,400 µmol m^{-2} s^{-1} (de Hoog, 1994). By terminating supplemental lighting in April once light sums of 12 to 14 mol m^{-2} d^{-1} were reached, production showed a considerable decline (Gislerød, 1997). Optimum production is only possible if and when all production factors are optimized.

Threshold light sums

In experiments with the cultivar 'Mercedes' (a very sensitive cultivar for blind shoots), it was demonstrated that providing a light sum of 3.5-4 mol m^{-2} d^{-1} resulted in virtually no flower development. From 4 to 8 mol m^{-2} d^{-1}, the largest increase in flowering was observed (Bakker, 1997). The lowest percent of blindness in the cultivar 'Mercedes' was observed when the light sum was 8.6 mol m^{-2} d^{-1} or higher, which corresponds with a light intensity of 200 µmol m^{-2} s^{-1} during a 12-hour lighting period (Maas, 1995, 1997).

When two shoots on pinched cuttings develop simultaneously this light sum is even higher: at least 11.7 mol m^{-2} d^{-1}, accumulated from a light intensity of 270 µmol m^{-2} s^{-1} for 12 hours. The percentage blindness for the upper shoot was 11%, while for the basal shoots it was 67%. The exact critical light sums for a mature crop are not known. From a physiological point of view, estimated minimum light sums of 12-13 mol m^{-2} d^{-1} are necessary, but these are certainly not optimal.

The effects of supplemental lighting depend not only on the intensity and duration of the lighting, but also on other factors such as air and soil temperature, carbon dioxide concentration, and plant or shoot density. When the number of shoots per square meter increases, a small change in the light intensity or light sum can have a significant impact on the percentage of blind shoots. This occurs even at high light sums of about 20 mol m^{-2} d^{-1} (Bredmose, 1997b). A relatively small increase in light sum from 17.8 to 21 mol m^{-2} d^{-1} reduced the percentage of blind shoots from 16 to 8% (average for the cultivars 'Lambada', 'Manhattan Blue', 'Red Velvet' and 'Sonia'). Increasing the number of plants per square meter from 100 to 178 (allowing one shoot per cutting) increased the percentage of blind shoots from 3 to 22%.

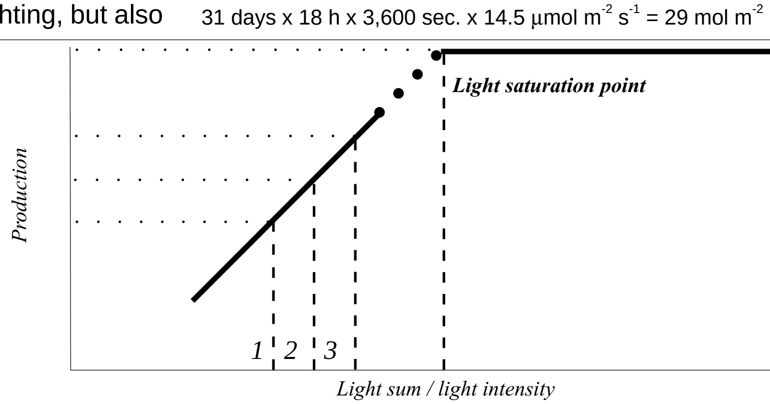
Lighting and production

Experiments with the cultivars 'Frisco', 'Sacha', 'First Red', 'Madelon', 'Sonia' and 'Charmilla' demonstrated that the number of stems and the harvested plant mass per square meter increased with 71-136% and 100-133%, respectively, in comparison with unlit crops if supplemental lighting was provided using an intensity of 100 µmol m^{-2} s^{-1} (De Hoog, 1998). Particularly for some large-flowered cultivars, stem mass significantly increased using a light intensity of 50 µmol m^{-2} s^{-1}.Doubling the light intensity from 50 to 100 µmol m^{-2} s^{-1}, however, did not result in doubling of the production based on number of stems or harvested plant mass. Comparing an unlit treatment with a treatment using a supplemental lighting intensity of 50 µmol m^{-2} s^{-1} showed a 71-95% increase in harvested plant mass, while comparing supplemental lighting intensities of 50 and 100 µmol m^{-2} s^{-1} showed an increase of 'only' 13-28%. In experiments with the cultivar 'Madelon' grown in The Netherlands during the winter, a linear relationship was found between the production and light sum (Van Rijssel, 1995) (Figure 6.10). A comparison can be made with Danish data (Bredmose, 1997a). Using a 20-hour photoperiod, an increase in light intensity in steps of 14.5 µmol m^{-2} s^{-1} resulted in an increase in the monthly production (per square meter) of 4.2 flower stems for the cultivar 'Frisco' and 2.6 stems for the cultivar 'Gabriella'. The lamps were turned on when the light level in the greenhouse dropped below 75 µmol m^{-2} s^{-1}. If during the winter 18 hours of lighting is provided, the monthly increase in the light sum for the extra 14.5 µmol $m^{-2}s^{-1}$ is:

31 days x 18 h x 3,600 sec. x 14.5 µmol m^{-2} s^{-1} = 29 mol m^{-2} .

Figure 6.10. ***Relationship between rose production and daily light sums.***

Under Dutch conditions (condition 1), providing extra light (conditions 2 and 3) year-round results in a linear increase in rose production. Thus, even during summer, crop photosynthesis is not saturated.



For the cultivar 'Madelon' (Van Rijssel, 1995), a monthly increase of 29 mol m^{-2} resulted in a monthly increase of production with 2.5 stems.

Since the cultivar 'Madelon' produced fewer but heavier stems compared to the cultivar 'Gabriella', the Danish results corresponded reasonably well with the Dutch data. In addition, the Dutch research demonstrated a linear relationship between the extra production and the electricity consumption for supplemental lighting (Van Rijssel, 1995).

Based on a total electric input of 460 watt for each 400 W SON-T lamp, an electric use of 100 kWh m^{-2} resulted in an extra yield of 795 g fresh mass or 27 stems per square meter (averaged for the period from week 40 through week 12 for the cultivar 'Madelon'). The fresh mass production varied from 8 g per kWh for weeks 40 through 44 to 15 g per kWh for weeks 8 through 12. A continued effect from supplemental lighting can generally be observed for another 4-week period but not much longer. When supplemental lighting was provided at an intensity of 45 µmol m^{-2} s^{-1} and a 16-hour photoperiod during weeks 48 through 52, this required an electric energy consumption of 18.6 kWh m^{-2}. This led to an extra yield of 18.6 x 10.6 g = 197 g m^{-2}. This resulted in eight additional stems at approximately \$0.33 per stem, or a return of \$0.14 per kWh.

Linear relationships can only be obtained when greenhouse environment, lighting intensity, lighting strategy, crop management, and shoot density are optimally adjusted.

General recommendations

Ultimately, how supplemental lighting will be applied (intensity, number of hours of lighting, photoperiod)

Converting instantaneous light levels and light sums

*For **high-pressure sodium** (SON-T Plus 400 W) light:*

1 µmol $m^{-2}s^{-1}$ = 85 lux = 0.2 Wm^{-2} PAR = 7.9 ft-c (1)

For the conversion of lux to footcandle: 1 ft-c = 10.76 lux
For lux and ft-c as basis, the conversions are:
1,000 lux = 11.8 µmol m^{-2} s^{-1} = 2.4 W m^{-2} PAR = 92.9 ft-c
1,000 ft-c = 126.6 µmol m^{-2} s^{-1} = 25.3 W m^{-2} PAR = 10.76 klux

Measurements by the Research Station for Floriculture and Glasshouse Vegetables in Aalsmeer, show variations from 11.9 to 13.4 µmol m^{-2} s^{-1} per 1 klux.
The number of µmol m^{-2} s^{-1} per klux increases as the lamps get older and the lamp voltage is increased.

*For **daylight**, the following conversion can be used:*

1 µmol $m^{-2}s^{-1}$ = 56 lux = 0.217 Wm^{-2} PAR = 5.2 ft-c (2)

For lux and ft-c as basis, the conversions are:
1,000 lux = 17.9 µmol m^{-2} s^{-1} = 3.9 W m^{-2} PAR = 92.9 ft-c
1,000 ft-c = 192.3 µmol m^{-2} s^{-1} = 41.8 W m^{-2} PAR = 10.76 klux
The type of weather plays an important part in this conversion, see Table 5.2

Light sum using HPS
1 MJ m^{-2} PAR = 5 mol m^{-2} = 118 klxh = 10,970 ft-ch ***(3)***

Daylight sum *(45% PAR of total radiation)*
1 MJ m^{-2} PAR = 4.6 mol m^{-2} = 71.9 klxh = 6,640 ft-ch ***(4)***

Converting supplemental lighting into biomass production. *Source: Van Rijssel, 1995.*

The energy use by a 400 W SON-T Plus lamp is 460 watt per luminaire.
This is converted into 3.11 mol m^{-2} of PAR light per kWh m^{-2}.
This PAR light is converted by the cultivar 'Madelon' into biomass (fresh mass) and can be expressed in gram or stems per kWh or per mol:
0.27 stems or 7.95 g per kWh, or
0.0868 stems or 2.56 g per mol.

is an economical decision. The average light intensity in The Netherlands is generally around 60 µmol m^{-2} s^{-1}. It has doubled during the last decade. Modern greenhouse operations, provide and intensity of 100 µmol m^{-2} s^{-1}. The maximum photoperiod varies from 16 to 24 hours. Usually it is limited to 20 hours due to local laws and regulations. The photoperiod is cultivar dependent.

Most lighting set points are based on outside global radiation, expressed in J cm^{-2} d^{-1}, as discussed below. In addition to the daily light sum, the photoperiod is also an important consideration for supplemental lighting.

If the daily outside light sum exceeds 1,000 J cm^{-2} d^{-1}, a 16-hour photoperiod is used, if it is less than 1,000 J cm^{-2} d^{-1}, a 20-hour photoperiod. In addition, it is important to know the light sum inside the greenhouse. When the greenhouse transmits 60% of the sunlight and 45% of sunlight is PAR, an outside global radiation of 1,000 J cm^{-2} d^{-1}, corresponds with and inside light sum of 12.4 mol m^{-2} d^{-1}. This light sum could be increased to at least 13.5 mol m^{-2} d^{-1} using additional supplemental lighting to a 16-hour photoperiod. In The Netherlands, from the beginning of November to mid-February this light sum cannot be achieved with commonly used lighting levels. In December, the total light sum can reach about 9.5 mol m^{-2} d^{-1} when 20 hours of lighting is provided at an intensity of 100 µmol m^{-2} s^{-1}. The minimum threshold value mentioned above could be achieved with a light intensity of 150 to 200 µmol m^{-2} s^{-1}, which are used in Norway. When operating the supplemental lighting system for 20 hours, the resulting light sums provided by the lighting system alone are 10.8-14.4 mol m^{-2} d^{-1}. In The Netherlands, lighting generally starts in mid-September and ends in mid-April.

Turning the lamps on or off

The set point for turning the lamps on and off is usually set at an outside global radiation of 300 to 350 W m^{-2} (DLV, 1999). The higher these set points, the longer the lighting period. From a production point of view, lighting until well into the summer can be beneficial. It is recommended to carefully analyze the number of lighting hours provided with respect to costs and benefits. An example of the calculation of the number of lighting hours is shown in Table 5.5. In addition, research has shown that when lighting is

Table 6.10. ***Vase life (in days) for 14 rose cultivars grown at different relative humidities (RH) and photoperiods.***
Source: Mortensen, 1999.

Photoperiod	18 hour			24 hour				18 hour			24 hour		
RH (%)	**75**	**83**	**91**	**75**	**83**	**91**		**75**	**83**	**91**	**75**	**83**	**91**
Amadeus	11.3	10.5	5.8	7.6	3.6	1.7	**Golden Gate**	15.4	15.4	12.8	14.7	12.0	9.9
Baronesse	11.8	11.2	7.9	7.4	4.6	4.3	**Kardinal**	11.6	9.5	10.0	9.7	7.9	4.4
Colinda	12.9	11.6	6.7	8.6	4.7	3.0	**Lambada**	10.1	9.2	7.7	8.1	6.8	5.3
Dream	13.0	14.0	11.5	11.2	8.2	7.5	**Orange Unique**	9.9	7.5	2.5	5.2	1.3	1.7
Escimo	13.5	13.5	11.0	11.2	9.8	7.1	**Prophyta**	15.0	11.7	7.1	8.4	7.2	4.4
First Red	11.7	10.4	9.3	10.5	7.8	4.7	**Miracle**	9.9	8.1	4.3	5.6	4.2	1.8
Frisco	16.3	15.7	14.1	15.4	13.2	10.7	**Sacha**	12.8	11.5	8.2	9.0	5.0	4.5
							Average	**13.0**	**12.1**	**9.1**	**10.0**	**7.5**	**5.6**

applied for several hours during the night, during summer production the color of certain cultivars can be greatly improved. Supplemental lighting should only be provided during the summer if the generated heat can be adequately utilized (Van Rijssel, 1995).

Disorders

The use of supplemental lighting usually increases the incidence of disorders. Excessive lighting (long photoperiods) may lead to curling of leaves, bent necks, and undesirable color changes of leaves and flower buds. Furthermore, disruption of the closing rhythm of the stomates may occur. This rhythm may even completely disappear when the dark period is shorter than 4 to 8 hours after extended periods of lighting. This sensitivity is cultivar-dependent: *e.g.* 'Frisco' is much less sensitive than 'Sonia'. When the latter cultivar was lit for 20 hours, the stomates remained open after harvest, even during darkness (Slootweg, 1991). Partly because of the development of larger leaves due to lighting, the transpiration increases, and therefore also the (post-harvest) uptake of preservatives and hydrating solutions. This may lead to excessive concentrations of sugars in the leaves causing leaf necrosis (Markhart, 1995). Maintaining a minimum dark period usually extended vase life, as was recently demonstrated for 14 cultivars (Mortensen, 1999). When the RH was increased from 83 to 91%, shoot fresh mass declined by an average of 11% for the 14 cultivars. Vase life declined with 12 to 75% when the RH was increased from 75 to 91% using an 18-hour photoperiod (Table 6.10). When the photoperiod was extended to 24 hours, the post-harvest quality of these cultivars decreased 31 to 78% and was closely related to water loss in the leaves. Reduced keeping quality as a result of higher RHs during production has also been observed in The Netherlands (Marissen, 1999).

Summarizing, supplemental lighting of roses increases:

- Production, measured in number of stems, dry and fresh mass of the stems. Reduction in blind shoots results in more harvestable stems.
- Quality. The flower stems are heavier and sturdier, reducing the risk of damage at harvest and packing, partly because the leaves are thicker (sun leaves). The number of petals in the flowers increases. Spray roses have more flowers per stem. Bicolored roses can be grown more easily with a better and more intense flower color. Often the vase life increases (cultivar dependent). Also, the development of black edges on the petals of the red mutants of the cultivar 'Calibra', *e.g.* 'Tiamo', 'Aruba', and 'Sacha' is reduced. This seemed to be caused by a low sugar and starch content of the buds (Marissen, 1997).
- Resistance against fungal diseases resulting in a lower usage of pesticides.
- Assortment of cultivars during winter production because summer cultivars can be grown.
- Competitive position with respect to production in countries closer to the equator.
- Uniformity of production. The production period is less dependent of the weather so that planning becomes more accurate and labor requirements are more even throughout the year.

Trachelium caeruleum

Year-round flowering is impossible without the use of supplemental lighting, as is the case with carnations. Daylength extension rarely leads to additional flower initiation in carnation because the light sums are too low. During summer, with high light levels, flower initiation occurs very quickly. These responses are similar for Trachelium.

Trachelium is planted from November through the end of July. Adequate crop height is obtained with temperatures between 16 and 21°C. Flower buds should not be initiated until plant height reaches 20 cm. To avoid high temperatures and premature flower bud initiation, the greenhouse should be whitewashed in mid-April for a planting in early April. Subsequent plantings should have the whitewash already applied, even when shade curtains are used. The whitewash should be removed by the end of July or the beginning of August to avoid delays in flower bud initiation. These cultural practices indicate the high light requirement. To obtain enough plant height during summer production, a SD treatment of several weeks can be applied directly after planting.

Lighting

Supplemental lighting with an intensity of 45-55 μmol m^{-2} s^{-1} results in heavier flower stems with improved branching and a slightly accelerated harvest date. The production period varies between three and five months, and the harvest period may extend over four weeks or longer.

Photoperiod

For bud initiation and development, Trachelium requires a photoperiod of at least 16 hours (Nijentap. 1997). The plant is bi-annual, but it can be forced to flower in one season. This is done through a long vegetative period. Daylength extension is necessary during production for most of the year.

Photoperiodic lighting

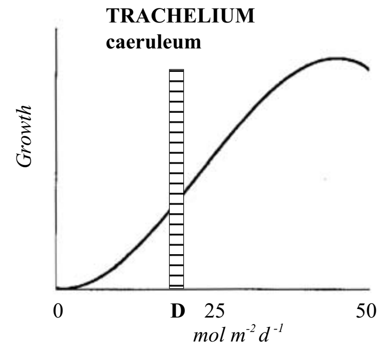
If the crop has not reached the visible bud stage by the beginning of August, photoperiodic lighting should be provided. If the buds have been initiated properly, photoperiodic lighting can be delayed until the second week of August. After August 1, daylength extension should be started one week after planting. This can be done either by supplementing the natural daylight to 18 hours, or by cyclic lighting with incandescent lamps (1.75 μmol m^{-2} s^{-1}) during 10, or preferably 15 minutes for each 30-minute period. For strong vegetative growth, a 22-24 hour photoperiod was needed (Vegmo, 1998).

The effect of a long photoperiod is most pronounced during August and September. This results in a higher percentage of flower bud initiation and more uniform flowering. By applying photoperiodic lighting through the end of the cropping cycle, more uniform flowering is obtained and a pyramid-like structure of the umbel can be avoided.

Installed wattage of incandescent lamps (150 W) and resulting light intensities at 2 m below the lamps.
Source: PBGA, 1996.

Light intensity (average) μmol m^{-2} s^{-1}	*Installed lamp wattage watt per 10 m^2*	*Number of lamps per 10 m^2 of floor area*
1.5-2.0 (1.75)	*15*	*1*

To obtain the same light intensities using 18 W compact fluorescent lamps, four times as many, and using 18 W fluorescent and low-pressure sodium lamps, three times as many lamps must be installed.



Trachelium is a LD plant with a critical daylength of approximately 16 hours.
This plant originates from the Mediterranean. SD conditions using an 11-hour photoperiod are maintained during the summer (except during seedling production) to postpone flower initiation and obtain height.
*The light requirement is very high. Below the threshold value (**T**) of 20 mol m^{-2} d^{-1}, delay in flower bud initiation can be readily observed.*

Tulipa hybrids

For production (forcing) of hyacinths, tulip, and daffodils, photoperiodic lighting rather than supplemental lighting is provided. The plant bulb supplies the developing flowers with sufficient nutrients. Photoperiodic lighting promotes good color and flower development. In production areas without natural daylight, a light sum of 60 Wh m^{-2} d^{-1} is required and can be provided by operating fluorescent lamps for 12 hours at a light intensity of 5 W m^{-2} PAR (23 μmol m^{-2} s^{-1}). A certain amount of blue light (as in fluorescent lamps) is required for satisfactory flower color (Gude, 1988).

Zinnia elegans

This quantitative SD plant is a native of Mexico. The light requirement is high. Optimal temperatures during production are 18 to 21°C. Norwegian experiments showed that year-round production is possible with a minimum light intensity of 105 μmol m^{-2} s^{-1}. The shortest production period (7.6 weeks) was obtained using a light intensity of 265 μmol m^{-2} s^{-1}, resulting in an annual yield of 100 stems per m^2 (Gartner Yrket 17/1996).

Table 6.12. *Desired light levels for growing of various cut flowers.*

	Light intensity 1	Light requirement $\mu mol\ m^{-2}\ s^{-1}$ 2	Light sum $mol\ m^{-2}\ d^{-1}$ 3 A	B
Alstroemeria	600 - 1,000	vh	13	20
Aster ericoides	800 - 1,200	vh	5	17
Bouvardia	-	h	5	-
Chrysanthemum	-	vh	5	17
Dianthus (carnation)	-	vh	15	20
Eustoma (Lisianthus)	-	vh	6	9
Freesia	600 - 1,000	m	4	17
Gerbera	500 - 700	h	7	-
Gladiolus	-	vh	13	-
Hyacinth*	-	l	-	1
Iris (Dutch)	-	h	5	-
Lilium (Oriental)	1,400 - 1,600	vh	4.1	-
Lilium (Asiatic)	-	vh	5.3	-
Lilium longiflorum	600 - 800	h	3.7	-
Narcissus*	600 - 700	l	-	1
Rose	1,000 - 1,200	vh	12-13	20
Trachelium	1,000 - 1,200	vh	-	20
Tulip*	-	l	-	1
Zinnia	600 - 800	h	-	-

**during forcing*

Column 1:

Optimum light intensity at the top of the canopy

Sources: Dole and Wilkins, 1999; Horn, 1996.

Column 2:

Light requirements

vh: very high: > 30 mol m^{-2} d^{-1}

h: high: 20-30 mol m^{-2} d^{-1}

m: medium: 10-20 mol m^{-2} d^{-1}

l: low: 5-10 mol m^{-2} d^{-1}

Column 3:

Minimum light sum. Below the indicated light sums (A and B), the crop can experience:

A. Blind shoots; delay in flower bud initiation

B. Delay in growth and development

6.2 Lighting Recommendations for Various Crops

6.2.7 Lighting of greenhouse vegetables

Introduction

Most important greenhouse vegetable crops have a very high light requirement of 30 mol m^{-2} d^{-1} or more. For this reason, seedling production in The Netherlands is performed during late fall and winter when natural light sums total 2-4 mol m^{-2} d^{-1}. During this period, under natural conditions, fruit set and growth is barely possible. For example, tomato fruits, when initiated before this period with low light sums, can still develop but slowly and at lower temperatures. Thus, production until well into January is possible. However, during January and February, the production of Dutch vegetables is very low (Figure 6.11).

In The Netherlands, seedling production is contracted out to specialized nurseries, equipped with supplemental lighting systems. This results in more vigorous plants with a larger leaf area, and consequently improved growth after transplanting. Unfortunately, the light intensity in production greenhouses is usually much lower compared to during seedling production (Figure 4.8). The extra vigor of the sun leaves developed during seedling production, can therefore not be optimally utilized.

In The Netherlands, production of greenhouse vegetables is also possible during the period from mid-November until mid-February, if sufficient lighting is applied. Furthermore, it can be greatly increased if supplemental lighting is applied during the remainder of the year, especially from September through March (Figure 6.11). Until recently, the interest in the use of supplemental lighting has been small, but it is

6.2.7 LIGHTING OF GREENHOUSE VEGETABLES

- ***Eggplant (Aubergine)***
- ***Cucumber***
- ***Lettuce***
- ***Sweet pepper***
- ***Tomato***

growing considerably. It appears, for example, more cost-effective to invest in supplemental lighting in The Netherlands than to set up and run a greenhouse operation in Spain. Which modern greenhouse operation can afford not to produce for three or four months out of the year?

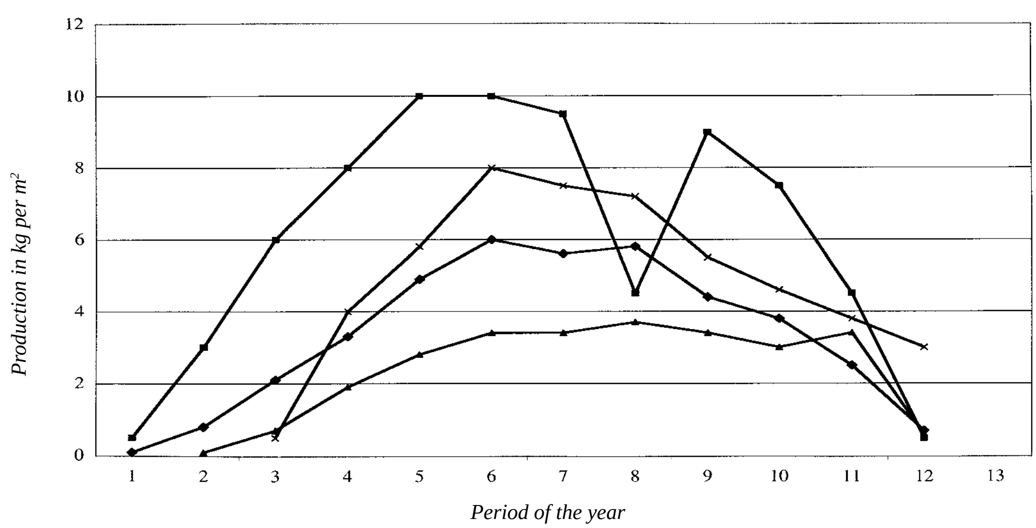
Cucumber

Introduction

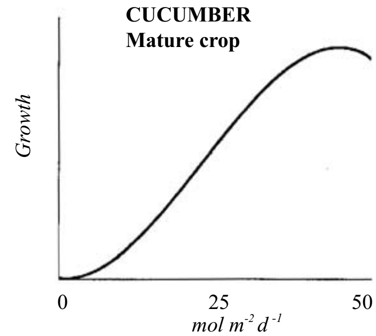
Greenhouse cucumber, tomato, and sweet pepper are all indeterminant plants. After a short vegetative phase, these plants continue with a generative phase, in which (in addition to leaves and (side) shoots) flowers are continuously being initiated and fruits develop. The fruits compete with one another and with the vegetative parts (leaf, stem, root) for the available products of photosynthesis (assimilates). The distribution of assimilates or dry matter over the various organs is an important factor determining production and quality.

During the growing season, amounts varying between 40 to 90% of the produced dry matter are dis-

Figure 6.11. ***Dutch greenhouse vegetable production during the course of the year expressed in kg of production per square meter per 4-week period.*** *Source: Quantitative Information for Greenhouse Horticulture 1997/1998 (KWIN, in Dutch).*
■ *Cucumber, planting in week 52 & 30,* ✖ *Tomato, high-wire, planting in week 51,*
▲ *Sweet pepper, red, planting in week 48,* ◆ *Eggplant, planting in week 48-52.*



tributed to the fruits. The dry matter distribution is regulated by the number of fruits on the plant. This number can vary significantly (Marcelis, 1994).
The number of developing fruits of cucumber plants is often artificially manipulated by removing the fruitlets from the axils. The plant regulates this in a natural way through abortion of the fruitlets within 10 days after flowering. The remaining number of young fruits (fruit load) appears to be related to the growth rate of the vegetative parts.
More dry matter was transported to the fruits at a temperature of 25°C than at 18°C with a similar fruit load. In the long run (weeks), the temperature had only a small effect on the dry matter distribution because fruit load declines at increasing temperature. Increasing light levels had the opposite effect in the long term (Marcelis, 1994). Using higher light levels, more dry matter was transported to the fruits because the fruit load became higher. Using lower light levels, fewer flowers developed into fruits. In addition, the developmental period of the fruits became longer (Schapendonk et al., 1984). Furthermore, new flowers and fruits developed at a lower rate.
Since at every node more than one flower develops, the formation of new flowers is directly related to the differentiation rate of the leaves, which partly determines the earliness of the first fruits. Early production (yield) is not only affected by environmental factors after transplanting but also by the production method of the young plants.



Cucumber belongs to the family of the Cucurbitaceae, to which also melon, squash and gherkin belong. The flower initiation is not daylength sensitive, but the sex expression of the flowers of certain cultivars is. The cucumber is monoecious (mail and female flowers occur on the same plant).
SD promotes the development of female flowers while LD promotes male. However, high light sums lead to more female flowers, while at low light sums combined with high temperatures more male flowers develop. The present commercial cultivars, however, are completely female.
Cucumber has a very high light requirement.

Seedling production and growth

Temperature and light intensity have an important impact on the rate at which leaves initiate and unfold (Schapendonk et al., 1984). But the effect of light is less direct compared to the effect of temperature. When lighting is applied during seedling production, plants grow faster after transplant and produce a larger early yield. Furthermore, the plants remain more compact so that they can be handled easier. During the winter and without supplemental lighting, a very long hypocotyl (stem section below the cotyledons) develops and plants become long, thin, and weak. To prevent this, plants should receive minimal lighting until two weeks after sowing (until re-spacing). The cost of lighting per plant is low because the plants are spaced close together. It is beneficial to continue lighting during the second half of the seedling production period (Van Uffelen, 1985).
The effects of lighting on growth are shown in Table 6.13. In this experiment at the Dutch Research Station for Floriculture and Greenhouse Vegetables, the objective was to obtain plants which are as uniform as possible at the time of transplant.
Using an air temperature (D/N) of 22°C, the unlit plants were sown two weeks earlier than the plants that received 24 hours of supplemental lighting. Despite this difference, the lit plants were significantly heavier at transplanting and their sum of the leaf diameter was larger. The same trends were observed at a temperature of 25°C. Furthermore, a 24-hour photoperiod appeared to be more beneficial to the young plants compared to an 18-hour photoperiod. The lit seedlings had bigger and firmer leaves. Although plant height hardly changed, the plant fresh mass increased due to thicker stems, leaves, and petioles. Table 6.13 shows that the yield was significantly improved with increased photoperiod (last columns).
Table 6.15 shows that the early and total production are highest of those plants that experienced a 16-

Table 6.13. ***Effect of lighting during cucumber seedling production on growth and development. Two temperatures were used during seedling production, and supplemental lighting was provided to extend the photoperiod past the natural day length.*** *Source: Van Uffelen, 1985.*

			At transplanting (January 2)		Production in kg/m^2	
Temperature	**Photoperiod**	**Sowing date**	**Plant mass (g)**	**Sum leaf diameter (cm)**	**March 1**	**March 29**
22^{0}C	natural	11/13	13	66	0.9	4.5
22^{0}C	18 hours	11/23	33	113	2.1	5.8
22^{0}C	24 hours	11/27	41	125	2.1	6.0
25^{0}C	natural	11/18	12	67	1.1	5.0
25^{0}C	18 hours	11/28	20	84	1.8	5.3
25^{0}C	24 hours	11/30	33	102	2.3	6.3

Table 6.14. ***Effect of supplemental lighting during seedling production on plant development.***
During seedling production, two light sums were applied: 7.9 and 5.3 mol m^{-2} d^{-1}. Intensities and photoperiods were varied. Lighting was provided with fluorescent lamps. Source: Durieux, 1997.

Photoperiod (h)/ **Intensity** (W m^{-2})	**Fresh mass** (g/plant)	**leaf area** (cm^2)	**leaf dry mass** (g/plant)
08h / 60 W	44.2	1,414	2.71
16h / 30 W	44.6	1,629	3.54
16h / 20 W	27.2	1,183	2.25
08h / 40 W	21.6	793	1.52

Table 6.15. ***Effect of supplemental lighting during seedling production on plant production (kg per investigated plants, number not stated).*** *During seedling production, a light sum of 10.9 mol m^{-2} d^{-1} was used. The light source was a mixture of HPS and MH lamps. Photoperiod (h) / Intensity (W m^{-2}). Source: Durieux, 1997.*

week	**16h-30W**	**8h-60W**	**16h-20W**	**8h-40W**
43	6.68	0.00	0.00	0.00
44	13.59	7.29	9.59	2.02
45	19.13	11.29	15.30	7.02
46	28.96	18.44	19.75	12.57
47	29.88	24.12	23.16	19.94
48	34.99	29.66	26.95	23.64
49	44.75	42.04	31.93	28.73

hour photoperiod and a light intensity of 30 W m^{-2} PAR during seedling production compared to an 8-hour photoperiod and a light intensity of 60 W m^{-2} PAR. The same trend was observed using another combination and a lower light sum. Plant mass (fresh and dry mass) and leaf area benefit from longer photoperiods (Table 6.14) according to Durieux (1997).

Production

Supplemental lighting has four important effects on production (Schapendonk et al., 1984):

1. The average period required for fruit development declines,
2. The average fruit mass at harvest increases,
3. The number of harvested fruits increases, and
4. Fewer fruitlets are aborted under high light.

The temperature also plays an important role. The initiation rate of leaves increases with temperature, so that light interception increases and, thus, the (early) yield.

The growth rate of cucumber fruit is highly determined by the temperature sum since the date of flowering. But the actual fruit weight depends on the supply of assimilates (Klapwijk et al., 1982; Marcelis, 1994). The higher the light sum, the quicker a given harvest stage is reached, as the following numbers indicate: the growing period is 24 and 17 days, at 5.5 and 10 mol m^{-2} d^{-1}, respectively (Schapendonk et al., 1984), and only 10 days at 30 mol m^{-2} d^{-1} or more (Gobeil et al., 1989).

The kg-production increases from three per square meter in February to 10 in May and June, every four weeks (Figure 6.11, Quantitative Information for Greenhouse Horticulture, KWIN 1997/1998). This is due to the effect of low and high light sums of 6 and 22-24 mol m^{-2} d^{-1}, respectively.

During period 12 (week 45-48) when the crop is terminated, production is only 0.5 - 1 kg per square meter and during period 1 (week 1-4) when cropping begins, it is also only 0.5 fruits per square meter. Annually, a production of 73 kg per square meter is achieved with two or three plantings.

Fruit abortion occurs when fruit set is followed by a period of assimilate shortage of more than eight days. The signal for abortion, however, comes from older, competing fruits. These fruits have priority in terms of assimilate distribution until their period of most intense growth is completed (Schapendonk et al., 1984).

Light requirements

Maximum yields are possible at light sums of more than 30 mol m^{-2} d^{-1}. For this reason, the light requirement of cucumber is considered to be very high. In The Netherlands, such light sums only rarely occur inside greenhouses.

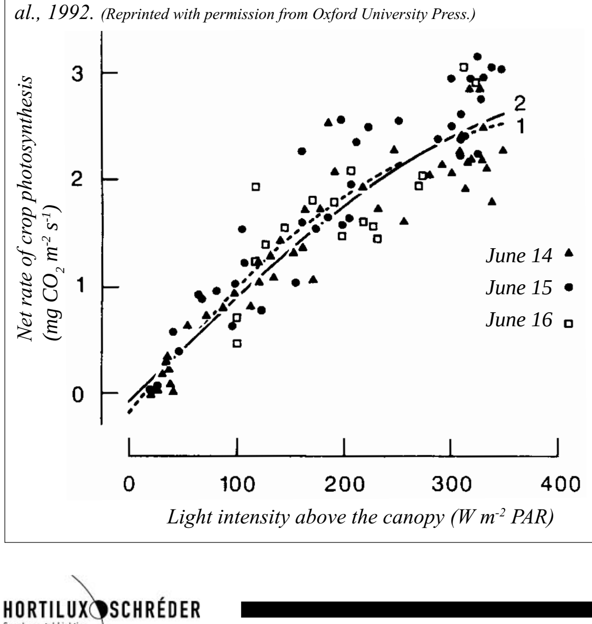
Growth and yield, measured in dry matter, highly depend on the net crop photosynthesis rate, which is still increasing even at light intensities above 350 W m^{-2} PAR or 1,610 µmol m^{-2} s^{-1} (Figure 6.12, Hand et al., 1992).

Until a light intensity of 200 W m^{-2} PAR or 920 µmol m^{-2} s^{-1} the relationship is linear (Figure 6.12). Measurements were conducted using an ambient CO_2 concentration during the month of June on 3 consecutive sunny days with light sums of approximately 38, 30 and 27 mol m^{-2} d^{-1}, respectively.

A steady fruit load is desirable because leaf photosynthesis declines when there are no fruits on the plant (Marcelis, 1994).

Carbon dioxide consumption also increases with higher light intensities. To maintain an ambient carbon dioxide concentration (350 ppm) at a light intensity of 350 W m^{-2} PAR, 95 kg CO_2 per hectare per hour is needed. In most cases, the ventilation rate is insufficient to provide this much carbon dioxide, and

Figure 6.12. ***The relationship between net crop photosynthesis and light intensity.***
Measurements were conducted using a mature cucumber crop grown in rows at the HRI in Littlehampton (UK). Statistically, two slightly different regression lines could be drawn. Source: Hand et al., 1992. (Reprinted with permission from Oxford University Press.)



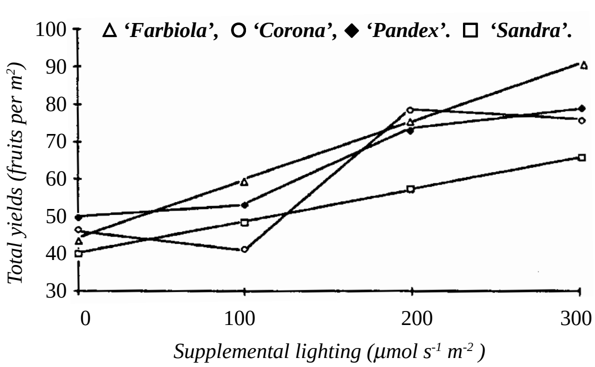
as a result, the concentration drops below the ambient level. If the CO_2 concentration is increased to 1,000 ppm, the net photosynthesis at a light intensity of 50 W m^{-2} PAR increases with 67% and at 350 W m^{-2} PAR with 80% (Hand et al., 1992). Based on these numbers the economic impact of lighting can be determined.

Lighting

Lighting in Canada (47°NL) with 300 µmol m^{-2} s^{-1} increased the yield after five months (December-May) with 47 to 90% compared to an unlit treatment, and depending on the cultivar (Figure 6.13). The number of fruits of the best cultivar 'Farbiola' increased from 41 to 78 fruits. The highest increase was obtained from the end of December until the end of February (an increase of 200% compared to unlit). Between the end of March and May 10, the production doubled (an increase of 100%). The response to higher light intensities was linear for 'Sandra' and 'Farbiola'. Surprisingly, the response of two other cultivars, 'Corona' and 'Pandex', was not linear. The productions of those cultivars increased strongly only between 100 and 200 µmol m^{-2} s^{-1} (Blain et al., 1987). On a year-round basis a total of 240 fruits per square meter can be harvested using optimum conditions and a light intensity of 300 µmol m^{-2} s^{-1}. In other experiments in Canada on a yearly basis with supplemental lighting of 180 µmol m^{-2} s^{-1}, a production increase of 80% was realized (Gosselin, 1988). From an economic point of view (1988), using a light intensity of 150 µmol $m^{-2}s^{-1}$ gave the highest return on investment.

The higher the supplemental light intensity the earlier the first yield. In Canadian experiments, the first production was realized on December 29, 23, 13, and 10, after planting on October 23 and using a supplemental light intensity of 0, 100, 200, and 300 µmol m^{-2} s^{-1}, respectively (Blain et al., 1987).

Figure 6.13. The relationship between production and supplemental light intensity. *Source: Blain et al., 1987. (Reprinted with permission of Amer.Soc.Hort.Sci.)*
Four cultivars received supplemental lighting (about 8 hours) to an 18-hour photoperiod using three intensities. On dark days, lighting was also given during the daytime. The harvest period was from 10 December until 10 May. The cultivars 'Sandra' and 'Farbiola' show a linear response throughout the different light intensities, while 'Corona' and 'Pandex' demonstrate a significant increase between 100 and 200 µmol m^{-2} s^{-1}. According to the researchers there exists a threshold value below which a production increase can not be expected.



Relationship between light sum and production

Experimental data from the Dutch Research Station for Floriculture and Greenhouse Vegetables (PBG) showed that a cucumber plant produces 3.4 to 4.3 g dry matter per MJ m^{-2} of PAR, and a carbon dioxide concentration of 364 and 620 ppm, respectively (Nederhoff, 1994). Based on the strong response of this crop to higher CO_2 concentrations, higher light utilization efficiencies are possible.

If it is assumed that on average 60% of:

$$4.6 \text{ g per MJ m}^{-2} \text{ of PAR (1 g per mol m}^{-2}\text{)}$$

is transported to the fruits, the effect of lighting on the production can be calculated.

Suppose that during winter 20 hours of supplemental lighting is provided with a light intensity of 150 µmol m^{-2} s^{-1}, this would result in an additional light sum of 10.8 mol m^{-2} d^{-1}. This light sum corresponds with an extra production in dry mass of:

$$0.6 \times 10.8 \times 1 \text{ g} = 6.5 \text{ g m}^{-2}.$$

Using an average fruit dry matter percentage of 3.5%, the extra daily fresh mass production is:

$$6.5 \text{ g} / 0.035 = 186 \text{ g m}^{-2} \text{ d}^{-1},$$

or on a weekly basis:

$$7 \times 186 \text{ g} = 1{,}302 \text{ g m}^{-2}\text{wk}^{-1}.$$

In these calculations, the dry matter distribution to the fruits, the dry mass of the fruits, and the light utilization efficiency are assumed to be constant.

Lighting and crop development

The growth rate and leaf initiation rate of young plants increase with the light sum (Klapwijk and Tooze, 1982). The number of leaves and stem length increase with photoperiod but internode length remains the same (Turcotte and Gosselin, 1987). These responses are cultivar dependent, *e.g.* 'Sandra' responds more strongly than 'Corona'. Lighting with a higher intensity (100 to 300 µmol m^{-2} s^{-1}) and using the same photoperiod, leads to an increase in the number of leaves, leaf thickness, stem length and dry matter content of the aerial parts (Blain et al., 1987). The leaf thickness also increases with the photoperiod (Turcotte and Gosselin, 1987). The leaves adapt to the light quantity. The mesophyll tissue (where photosynthesis takes place) is more developed and often consists of two cell layers (Blain et al., 1987). As a result, the photosynthesis capacity increases (Louwerse et al., 1977; Armitage et al., 1983). The anatomy and the shape of the leaves are more determined by the light sum than by the intensity (Chabot et al., 1979).

Photoperiod

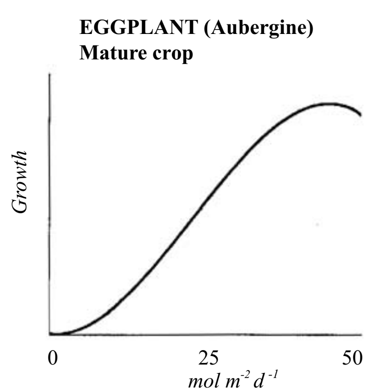
During the period from sowing to transplant, a 24-hour photoperiod is feasible. But due to local regulations ('light pollution') or financial considerations, usually a 20-hour photoperiod is maintained in The Netherlands.

During production, the growth stimulating effects of supplemental lighting are mainly determined by the length of the photoperiod, from 20, to 18, to 16, to 14 to 10 hours (Turcotte et al., 1988). The 20-hour photoperiod results in the highest production and growth rate. It does not matter when the dark period is applied: in the middle of the night, at the beginning or towards the end of the night, or distributed over beginning and end.

Using a 20-hour photoperiod, the plants produced two more full-grown fruits at the start of harvest compared to using 14 or 16-hour photoperiods. Using an 18-hour photoperiod, the plants produced slightly less than one more full-grown fruit at the start of the harvest period. The conclusion was that the optimal photoperiod is somewhere between 18 and 20 hours (Turcotte et al., 1988). The earliness is closely related to the light sum (Schapendonk et al., 1984). Norwegian research demonstrated that, as the plants get older, they develop a need for a dark period. For mature plants a night extension of 0 to 4 hours (using an equal light sum) was responsible for a production increase of 50% (Grimstad, 1990).

Quality

Mass, size, color, and firmness of the fruits are used as indications of quality. Mass and size vary during the course of the year. During the summer, fruits are harvested at a bigger stage than during the winter, because of the increased growth rate of the fruit during the summer. But also price, plant load, and fruit shape (length/thickness ratio) play an important role. At harvest, fruits are not ripe (from a plant physiology point of view), and not fully developed. If harvested at a premature stage, the fruit is more likely to develop weak necks and shriveled skin. However, if harvested at a later stage, the fruits yellow sooner (Janse, 1994). As light levels are increased, fruits can be harvested sooner at an earlier stage of development with a high length/thickness ratio (Marcelis, 1994). A positive relationship is expected between fruit quality and dry matter content, which is about 3.5% (Heuvelink et al., 1989). Young fruits have a higher percentage of dry matter: approximately 6% after 5 days (Marcelis, 1994). This percentage declines with decreasing irradiation, increasing temperatures, and higher plant load and age.



Eggplant belongs to the family of the nightshades or Solanaceae.
The temperature and light requirement are very high.
Eggplant requires a minimum 4-hour dark period.

Keeping quality

The intensity and color of the light significantly affect the color and keeping quality of the fruit (Lin et al., 1996). This was apparent from shading experiments in Vancouver, Canada. The keeping quality of fruits grown under full light (100%) and under shade (31%) was 8.5 and 1 day, respectively. Red light promoted the keeping quality. Therefore, lighting with HPS lamps has a positive effect.

Fruits from an open crop canopy have a better keeping quality than fruits from a dense crop. In addition, fruits grown near the top of the plant have a better keeping quality than those grown near the base of the canopy. The differences in keeping quality are related to the chlorophyll content in the fruit skin. Maximum shelf life is generally measured until the fruit skin starts to yellow. After harvest, the chlorophyll gradually decreases. Therefore, fruits with a higher chlorophyll content remain green longer. This is the case with fruits that received significant amounts of light. Red light also stimulates chlorophyll formation, which is particularly important under low-light conditions.

In conclusion, lighting with high-pressure sodium lamps and an open canopy structure favor the keeping quality of cucumbers.

Summary and recommendations for lighting

It is recommended to use heavy seedlings with large leaf areas. This results in a higher early and total production. During seedling production, supplemental lighting can best be provided using 20-24 hour photoperiods and a relatively high light intensity of at least 40-50 $\mu mol\ m^{-2}\ s^{-1}$. The longer the photoperiod, the better. When lighting is provided during production, the light intensity during seedling production should adjusted accordingly. For year-round production, at least 150 $\mu mol\ m^{-2}\ s^{-1}$ is needed. The optimal photoperiod for a mature crop is between 18 and 20 hours. Plant load and density should be adjusted to the provided light intensity. For good fruit quality and shelf life, an open crop structure is preferred.

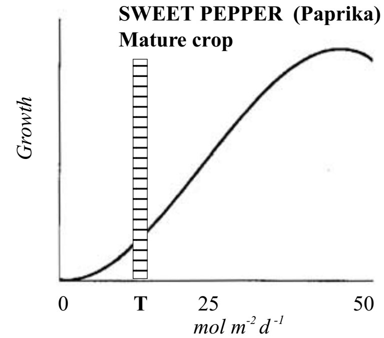
HPS light has a favorable influence on plant and fruit keeping quality.

Eggplant

Little research describing the use of supplemental lighting during eggplant production is reported in the literature. Based on production pattern and flower bud abortion during January and February, the lighting requirements correspond with those of other vegetables. Lighting is only feasible if applied at a sufficiently high intensity, for example 150 $\mu mol\ m^{-2}\ s^{-1}$. Although a 24-hour photoperiod can be maintained for a short time period, a maximum of 20 hours is maintained to avoid chlorosis and leaf damage. Lighting during seedling production had an advantage compared to the unlit control plants. Furthermore, flower bud abortion was significantly reduced: instead of 60%, 'only' 35% during the period from 6 February to 20 March (Maaswinkel, 1983, 1984).

Lettuce

This crop is sensitive for temperature, photoperiod and light. Therefore, an appropriate cultivar should be selected for each growing period. Although lettuce is a quantitative long-day plant, there are big differences between types and cultivars. European butterhead cultivars tend to show linear decreases in time to flowering with increasing daylength across the entire daylength range. Winter grown cultivars, are more susceptible to bolting than those adapted to summer conditions. American crisphead cultivars appear to have little response to photoperiods between 10-13 h, but are sensitive above this range. A third group is nearly day-neutral (H.C. Wien, 1997).
Lettuce is a temperate sun plant with a very high light requirement which can adapt itself to different light levels. Leaf photosynthetic rates of plants grown at 1,800 $\mu mol\ m^{-2}\ s^{-1}$ still increased at 1,400 $\mu mol\ m^{-2}\ s^{-1}$, while those grown at 720 $\mu mol\ m^{-2}\ s^{-1}$ did not. In the latter case photosynthesis was already saturated at 400 $\mu mol\ m^{-2}\ s^{-1}$. This is without additional CO_2, which has an enormous impact on growth (He Jie, 1998). As long as adequate levels of water and nutrients are available, increasing temperatures between 10 and 30°C, and increasing light sums up to 54 $mol\ m^{-2}\ d^{-1}$ speed up the number of leaves formed per unit time (H.C. Wien, 1997). This also translates into larger plant biomass and greater harvested yield.
Rootzone temperatures between 14 and 20°C (or under 25°C He Jie, 1998) are required for head formation, reduction of open heads, bolting or stalk formation (Maaswinkel et al., 1987, Jensen, 1990).
Temperatures (air) considered optimum for growth average 18°C, with a range from 24 to 7°C (H.C. Wien, 1997). Higher temperatures result in a high incidence of tipburn, bolting and the formation of loose, 'puffy' heads. Under low light, leaves tend to be long and narrow. As light levels increase, their shape becomes progressively broader, with a reduced length: width ratio. High temperatures combined with high light conditions enhance leaf width, and reduce it when combined with low light conditions.
Rapid soil cover after planting is important to accelerate growth. Light interception can be maximized by growing plants in Styrofoam blocks positioned on top of Styrofoam floaters that float on tanks of nutrient solution. This allows the plants to be respaced without disrupting growth. By providing a fixed light sum of 17 $mol\ m^{-2}\ d^{-1}$, heads with a desired weight of 150 g can be harvested after 5 weeks after sowing (Both et al., 1999; Albright et al., 2000) . The supplemental lighting intensity is 200 $\mu mol\ m^{-2}\ s^{-1}$, but growers use lower intensities (Ithaca). In the first 11 days young plants stay in a growth room (615 plants per m^2) at a photoperiod of 24 hours. In the greenhouse the number of plants per m^2 decreases from 81 to 28, 21 days after seeding. For 'regular' planting and harvesting light sums of 12-13 $mol\ m^{-2}\ d^{-1}$ or higher are needed, below this threshold growing periods increase very fast. This means additional lighting with 150 $\mu mol\ m^{-2}\ s^{-1}$ or more in months with lower light sums.



Sweet pepper belongs to the family of Solanaceae or nightshades.
Sweet pepper is native to Brazil and Central America. The initiation of leaf primordia is not affected by photoperiods between 7 and 15 hours. At a 24-hour photoperiod, this initiation is delayed by 5-9 days. Although this is considered a quantitative SD effect, in general sweet pepper is regarded as DN. The number of leaves until the first flower is 8 to 10. High night temperatures delay or prevent flowering.
*A mature crop has a very high light requirement. Below 12 $mol\ m^{-2}\ d^{-1}$ (**T**) the incidence of flower abortion strongly increases, depending on plant load.*

Sweet pepper

Introduction

In The Netherlands, sweet peppers are generally grown with a two- or three-stem system using a soilless substrate which results in excellent quality and yield. When the crop is vigorous enough, a three-stem system is used reducing the total number of plants. The optimum number of stems per m^{-2} is 6-6.5. Planting is often done only once a year, between the end of November and the middle of January, with the first half of December as the most important transplanting period. In November, the plants, which have reached a length of more than 3 m, are removed from the greenhouse after a production period of about 11 months. When the plant has developed a sufficient number of leaves and root system, the first fruit set is allowed (usually during the first half of January) depending on the planting time. During this period, the solar radiation increases and the plants can generally produce enough assimilates (sugars) to support fruit development. One leaf and one flower or two leaves and two flowers per side shoot are retained, to regulate fruit load. Through April, each shoot is allowed to retain one flower, but thereafter two flowers per shoot are retained. Too much fruit pruning leads to additional vegetative growth, resulting in taller plants, thicker stems, and bigger, heavier leaves. About 35 days after fruit set the fruit skin gets tight and the fruit becomes green. At that stage, green fruits can be harvested. Harvesting red fruits requires another 2-3 weeks. During the winter season, (three to four months), sweet peppers are not produced in The Netherlands.

Fruit set

One challenge for the sweet pepper producer is that fruit production comes in cycles. For example, after the first two to three flowers per stem have set, fruit set stops. This is because the developing fruitlets require large amounts of assimilates (sugars). As soon as the fruits are almost mature, this high sugar requirement declines. As a result, new flowers can be set which form the second fruit set cycle. Between these cycles blind nodes are formed, because the flowers have fallen off. When the natural light quantity increases, the time period between successive cycles becomes smaller. Nevertheless, the cyclic pattern remains noticeable. By variations of the planting times (during December and January), the harvest of the first fruit set can be manipulated somewhat. But during the course of the year, all plants start following to the same rhythm. For example, in The Netherlands, all plants show flower abortion as a result of light deficiency. This results in periods with high and low production, and, consequently with low and high prices, respectively.

Flower abortion is not only controlled by a sugar deficit, but also by compounds produced by the seeds inside the developing fruits. Seedless cultivars show a more regular fruit set and production, but they are not yet available on the commercial market (Heuvelink, 2000). Fruit thinning can also result in more regular harvesting intervals.

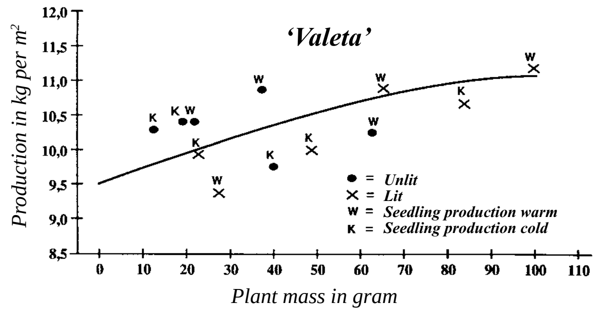
Effect of plant size on subsequent production

Sowing for the early (heated) crop is done in the beginning of October. The seedling stage is 50-55 days, using some supplemental lighting. At that point, the plants weigh approximately 30-40 g. Plants that are 30-35 days old are also used. The bigger the plants at transplanting, the earlier and larger the production (Table 6.16 and Figure 6.14; Van Uffelen et al., 1989). How this larger plant size is achieved is irrelevant (Van Uffelen et al., 1989).

The temperature during seedling production and/or the use of supplemental lighting do not affect production, but only production time. Lighting during seedling production does not adversely affect production potential (Figure 6.14).

Lighting with an intensity of approximately 3,200 lux or 37 μmol m^{-2} s^{-1} after potting can reduce the seedling production period with 14 to 18 days, when lighting is provided immediately after sowing. As a result of lighting, the leaf area strongly increases even though

Figure 6.14. ***Relationship between plant mass at transplanting (December 12) and total production on July 25 (Naaldwijk, The Netherlands).*** *Source: Van Uffelen et al., 1989. (Reprinted with permission from Elsevier Publishers.)*



the leaves do not get much thicker. Plants sown in October and intended for the earliest plantings are usually lit from sowing through delivery. Later sowings are often partially lit, *e.g.* from seeding until spacing, to maintain an average fruit set and to prevent the flowers from becoming to large. Otherwise, many malformed fruits develop. This points to the fact that lighting conditions at the beginning of fruit production should correspond to those during seedling production. This is also true for lighting during the remaining production period. The best method seems to be to continue the same lighting strategy throughout the crop cycle, resulting in the formation of leaves that are adapted to higher light levels and that have high light use efficiencies.

In Canada, lighting during seedling production (April/May) was provided at an intensity of 100 μmol m^{-2} s^{-1} from 02:00-10:00 hour to maintain a 16-hour photoperiod. Using this strategy, the plant dry mass was greatly increased. Combined with a CO_2 concentration of 900 ppm, this led to an increase of 42 to 66% compared to an unlit treatment without CO_2 enrichment. The early yield after transplanting was consequently increased with 11% (Demers, 1994).

Photoperiod

Early experiments showed that flower initiation is hardly influenced by photoperiods between 7-15 hours (Auchter, 1924; Cochran, 1942). At a 24-hour photoperiod, flower initiation is delayed by 5-9 days. Based on these results, sweet pepper can be regarded as quantitative SD plant.

Seedlings develop flower buds after 8 to 10 leaves

Table 6.16. ***The effect of lighting during seedling production on plant development and yield.*** *Lighting during seedling production with an intensity of 3,200 lux (37 μmol m^{-2} s^{-1}) and two sets of Day/Night temperatures were applied: 23-23.5/21-21.5°C (warm) and D/N temperatures of 2°C lower (cold). Source: Van Uffelen et al. 1989.*

Seedling treatment			Plant at delivery			Yield in kg per m²			
Sowing date	Lighting	Temperature	Plant mass *(g)*	Leaf area *(cm²)*	number flowers	April 18	May 30	July 25	Fruit mass *(g)*
Oct 7	-	warm	61.3	1290	0.5	1.56	5.16	10.22	175
Oct 7	-	cold	39.7	869	0.2	0.83	4.83	9.79	171
Oct 13	+	warm	100.5	1839	1.5	2.24	5.23	11.20	165
Oct 13	+	cold	83.5	1415	1.3	1.91	5.49	10.72	178

(Rylski, 1972). Subsequently, the main stem splits into two or three shoots, which, after development of an internode, end in a flower bud. At both sides of this node, little side shoots are formed, which also end in flower buds, etc.

Photoperiod and yield

In Canada and New York, lighting experiments have been conducted with the cultivar 'Delphin' to investigate the effect of the photoperiod on yield (Demers et al., 1998). Planting occurred on December 2 and red fruits were harvested from March 3 through July 16. The supplemental lighting system was turned on during the day provided the temperature did not exceed a certain set point. These experiments showed that extending the photoperiod from 16 to 20 hours increased yield. A 24-hour photoperiod during fruit production resulted in a decline compared to a 20-hour photoperiod. This was despite the fact that with continuous lighting 5-11% more light energy was provided. The average fruit mass was highest using a 16-hour photoperiod.

In New York, 14 and 24-hour photoperiods were used and planting occurred on January 17. The cropping cycle was completed on May 14. During the first production period (through the end of March/beginning of April), growth and yield increased under 24-hour lighting compared to under a 14-hour photoperiod. The longer photoperiod provided more light energy (45-27%). After 7-8 weeks, plant growth declined under the 24-hour photoperiod compared to the 14-hour photoperiod. At the end of the experiment, plant mass and yield of plants grown under a 14-hour photoperiod were equal to or higher than those for plants grown under 24-hour lighting. It may be feasible to provide continuous lighting during several weeks during the darkest months, to create extra growth, followed by 20-hour photoperiods. However, this needs to be tested first because there might be adverse effects later in the growth cycle. After 12 weeks (end of April) there was some incidence of leaf malformation, but no chlorosis. Halfway during the production period, in April/May, the plants grown under 14-hour photoperiods were longer (longer internodes), while those grown under 24-hour photoperiods had more internodes. Leaf disorders (blistering) had also been observed in other experiments using 20-hour photoperiods (Demers et al., 1991/1999), as well as leaf chlorosis and leaf drop using 24-hour photoperiods (Nilwik, 1981).

The starch and sugar content in the leaves increases when continuous lighting is provided compared to 14-hour photoperiods. Accumulation of those compounds can lead to a decline of growth. Changing photoperiods and/or fruit thinning did not change the pattern of sugar and starch accumulation in the leaves.

The experiments in New York were conducted at very high light sums without additional CO_2 enrichment. For the 14-hour photoperiod, the light sum varied between 25.7 mol m^{-2} d^{-1} in February to 42.4 mol m^{-2} d^{-1} in May. The light sums for the 24-hour photoperiod were 37.2 and 53.9 mol m^{-2} d^{-1}, respectively. An explanation may be found from the fact that growth reaches saturation at a light sum of 37 mol m^{-2} d^{-1} (April). Moreover, the dark period allows the plant to discharge assimilates. In The Netherlands, light sums rarely exceed 30 mol m^{-2} d^{-1}, allowing for the use of a 20-hour photoperiod.

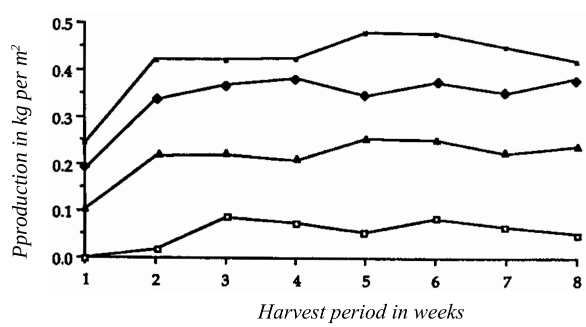
Lighting and yield

In Canada (Québec) experiments were performed with supplemental lighting during the production phase using intensities of 75 and 125 µmol m^{-2} s^{-1} and 16 and 20-hour photoperiods (Demers et al., 1991). Planting occurred on November 4 using 3.3 plants per square meter following the two-stem system. In December, the natural light sum of 5 mol m^{-2} d^{-1} is twice as high compared to The Netherlands. In March, the light sum is 16.6 mol m^{-2} d^{-1}. During December, supplemental lighting was applied for almost 16 and 20 hours, and during March slightly more than 11 and 15 hours.

In December, the total light sum was increased to 9.3 and 13.9 mol m^{-2} d^{-1} using a 15.8-hour photoperiod and a light intensity of 75 µmol m^{-2} s^{-1}, or using 19.8 hours and 125 µmol m^{-2} s^{-1}, respectively. Red fruits were harvested during eight weeks from January 30 through March 20 (Figure 6.15). Higher intensities and longer photoperiods increased the (weekly) production. Particularly during the first two weeks, lighting showed very distinct benefits compared to the control treatment. The average natural light sums of 5 and 8 mol m^{-2} d^{-1} in December and January, respectively, were apparently marginal for fruit set and fruit growth. The increase from 5 to 9.3 mol m^{-2} d^{-1} (using a light intensity of 75 mol m^{-2} d^{-1} and a 15.8-hour photoperiod) in December and the continued increase of light sums during the following months, quadruplicated the early and total yield. When a 19.8-hour photoperiod and a light intensity of 125 µmol m^{-2} s^{-1}

Figure 6.15. ***The effect of lighting on the weekly production of sweet pepper.*** *Source: Demers et al., 1991. (Reprinted with permission from Agricultural.Institute of Canada.) In Québec, transplanting was performed on November 4 followed by a harvest period from January 30 through March 20 (8 weeks). The lowest line represents the production without lighting (ambient), the remaining lines represent increasing light sums.*

■ *125 µmol m^{-2} s^{-1}, and a 20-hour photoperiod*
◆ *125 µmol m^{-2} s^{-1} and a 16-hour photoperiod*
▲ *75 µmol m^{-2} s^{-1} and a 16-hour photoperiod*
□ *ambient light*



were used, the production increased seven to eight times compared to the unlit control treatment. Cultivar differences were observed only using the higher light sums (> 12 mol m^{-2} d^{-1}). The conclusion from this experimental data is that for reasonable production during the winter, light sums are required of more than 12 mol m^{-2} d^{-1}. This can be achieved in The Netherlands during December by providing supplemental lighting with 150 µmol m^{-2} s^{-1} during 20 h.

Yield

The more light energy the plant receives, the higher the yield (Figure 6.15). Sweet pepper has a very high light requirement and can be grown at high light sums (see the section on photoperiod and yield). Below a light sum of 12 mol m^{-2} d^{-1}, light becomes a limiting factor for growth (see previous section). In The Netherlands, the natural light sum inside the greenhouse is lower than 12 mol m^{-2} d^{-1} during the period between the end of September and the end of March. The fruit set cycles are probably determined by days when the light sum is (far) below 12 mol m^{-2} d^{-1}. Combined with a high plant load, these conditions result in flower bud abortion. As a result, subsequent fruit settings are synchronized. If planting occurs in April and May (Figure 6.16), the rhythm of fruit set is not disrupted. During the following production period, the daily light sum rarely drops below 12 mol m^{-2} d^{-1}. Commercial growers producing sweet pepper year-round should provide a minimum daily light sum of 12 mol m^{-2} d^{-1} in order to control the timing of the production cycles.

Growth rate and light utilization

Sweet pepper plants grow slowly, compared to other fruit vegetable crops (Table 6.17). The light use efficiency (LUE) is also much lower. To calculate the effect of lighting on crop production, the LUE can be used. The LUE was reported as 1.7 and 2.1 g MJ^{-1} PAR at a CO_2 concentration of 306 and 450 ppm, respectively (Nederhoff, 1994). The crop responds strongly to carbon dioxide enrichment, so that the LUE could even be higher. Therefore, for the following calculations a value of 2.5 MJ^{-1} PAR is used (20% higher).

Relationship between light sum and production

As starting point, a dry matter increase is assumed of: 2.5 g per MJ PAR or 0.54 g per mole.

About 60% of this is distributed to the fruits, especially when CO_2 enrichment is provided (Nederhoff, 1994): 60% of 0.54 g = 0.32 g per mole.

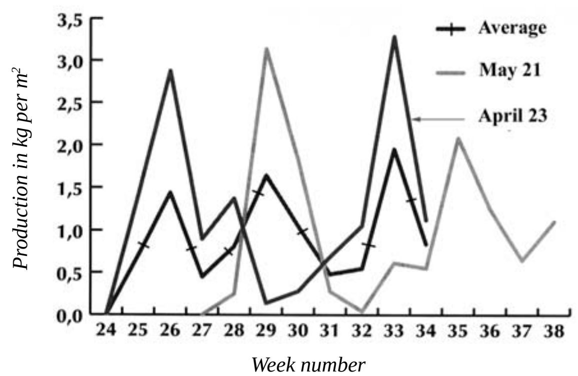
The average dry matter content of sweet pepper fruits is relatively high compared to other crops: 8.5% (Heuvelink, 1989).

Table 6.17. ***Growth rate and light use efficiency.***
The increase is expressed in dry matter. Source: Nederhoff, 1994.

Crop	Growth rate $g\ m^{-2}\ d^{-1}$	Light Use Efficiency $g\ MJ^{-1}$	CO_2 dpm
Cucumber	9.9 - 12.3	3.4 - 4.3	364 - 620
Sweet pepper	4.56 - 5.15	1.7 - 2.1	306 - 448
Tomato	14.9 - 17.5	2.8 - 3.4	370 - 510

Figure 6.16. ***The harvest pattern (production cycles) of sweet pepper.*** *Source: Heuvelink et al., 2000. (Reprinted with permission from Elsevier Publishers.)*

The production peaks of a crop planted on May 21 occur during the production dips of a crop planted on April 23. The result is a much more stable production pattern (average).



Therefore, the fresh fruit mass production per mole is then: 100/8.5 x 0.32 g = 3.8 g per mole.

If, for example, supplemental lighting is provided using a light intensity of 150 µmol m^{-2} s^{-1}, and a 20-hour photoperiod, the additional light sum is 10.8 mol m^{-2} d^{-1}. This additional daily light sum results in an increase of the fresh fruit mass of:

10.8 x 3.8 g = 41.0 g.

In order to remain profitable, this increase in yield has to be higher than the extra costs required for the operation of the supplemental lighting system.

The above increase in fresh fruit mass per mole of light can be compared with the weekly yields reported in Figure 6.15. During production in Canada, the total light sum, using a 20-hour photoperiod and a light intensity of 125 µmol m^{-2} s^{-1}, varied from 13.9 mol m^{-2} d^{-1} in December to 23.5 mol m^{-2} d^{-1} in March (approximately 18 mol m^{-2} d^{-1} on average). At the beginning of March, the Canadian production was reported at approximately 470 g per week, which roughly corresponds with the above calculation: using an average light sum during the period of fruit growth of 18 mol m^{-2} d^{-1}, the fresh fruit mass production is:

18 x 3.8 g = 68.4 g per day or
68.4 g x 7 = 478.8 g per week.

Recommendations

Plants that are bigger at the time of transplant produce earlier and consequently more fruits. During seedling production, lighting can be provided using a 20-hour photoperiod and a minimum light intensity of 40 µmol m^{-2} s^{-1}. Conditions during seedling production should match those during fruit production.

Fruit production increases linearly with the light sum. In The Netherlands, lighting with an intensity of 150 µmol m^{-2} s^{-1} and a 20-hour photoperiod allows for fruit production during the winter, independently of weather conditions. As a result, the harvest cycles can be somewhat manipulated by the grower. The minimum required light sum is 12 mol m^{-2} d^{-1}.

Tomato

Introduction

Tomato yield depends on factors like plant quality, growing technique, and environment conditions. Soilless production, the high wire system, and constantly improving climate control systems, have significantly increased annual fruit yield to 55 kg per square meter in The Netherlands. Even higher annual production is feasible. Using supplemental lighting during the winter months, year-round production becomes possible by extending the production season by at least three months. As a result, the production may increase to 92 kg per square meter using a light intensity of 10 klx or 118 µmol m^{-2} s^{-1} (Van den Berg, 2000).

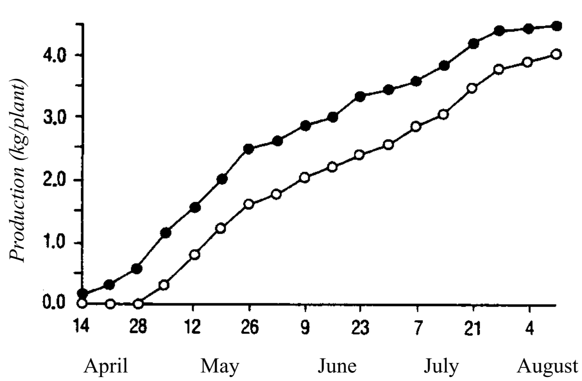
Effects of seedling quality

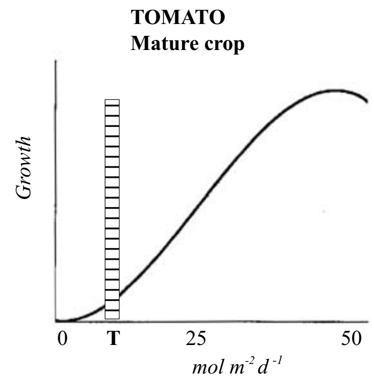
It has been discussed earlier that the quality of the transplants is very important for plant yield (Section 6.2.2). Figure 6.17 shows that the yield per plant continues to remain larger when lit seedlings are used. In trials in Québec showed that the initial yield from plants transplanted on January 25 was increased by 100%. The plants were lit using a light intensity of 100 µmol m^{-2} s^{-1} and a 17-hour photoperiod (05:00-22:00 hour) during seedling production and early growth, *i.e.* from seeding to a plant with the first flowering truss (Figure 6.19). Plant mass and leaf area increased very strongly while the leaves became thicker. During these experiments, flower abortion on the first truss was reduced by 11% (Boivin, 1987). In The Netherlands, plant mass and number of leaves below the first truss (leaf area) are used as quality characteristics of transplants. It is important that young plants have a big and firm leaf canopy. As result of lighting the canopy adepts, so that it is recommended to adjust the lighting intensity during seedling production to the intensity during fruit production.

Crop photosynthesis

Crop photosynthesis is rarely saturated under Dutch circumstances, even during the summer. In the

***Figure 6.17.* Cumulative yield of a January planting for lit (solid markers) or unlit (open markers) plants during seedling production.** *Source: Boivin et al., 1987.*
(Reprinted with permission of American Society of Horticultural Science.)





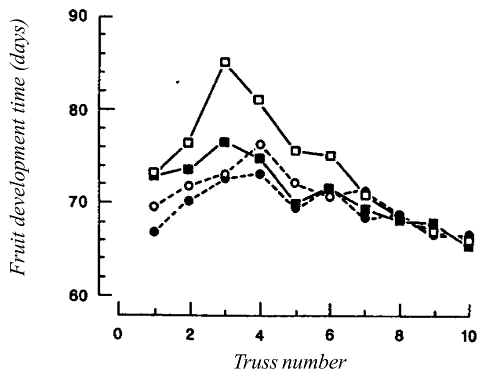
Tomato is a member of the Solanaceae or nightshade family. It is a native of the coastal plains from Ecuador to Chile in South America. The crop was domesticated in Mexico and bred for the production of tomatoes.
Tomatoes have no clear photoperiod sensitivity. The flower initiation is photoperiod neutral and takes place autonomously. Some environmental factors have some influence. At certain fixed light sums, flowering is stimulated by SD. For this reason, tomato is sometimes referred to as a quantitative SD plant.
Vegetative growth is promoted by LD. The number of leaves below the first truss is reduced by high light sums and low temperatures.
*During the production phase, the incidence of reduced fruit set and flower or truss abortion strongly increase at levels below 3.1 mol m^{-2} d^{-1} (**T** = threshold value).*
A mature crop has a very high light requirement.

greenhouse, the light intensity around noon is generally not more than 740 µmol m^{-2} s^{-1} (Table 5.4) with a few peaks of 1,400-1,500 µmol m^{-2} s^{-1}. Measurements at a light intensity of 1,400 µmol m^{-2} s^{-1} showed that tomato crop photosynthesis is not yet saturated (Heuvelink, 1996). In The Netherlands, the natural daily light sums inside the greenhouse do not exceed far above 30 mol m^{-2} d^{-1}, which is too low for maximal yields. Therefore, lighting with a minimum intensity of 100 µmol m^{-2} s^{-1} and a 16-hour photoperiod (resulting in an additional light sum of approximately 5.8 mol m^{-2} d^{-1}) is required to achieve reasonable growth during the winter.

Rate of flowering

The rate at which flower trusses are initiated is mainly determined by temperature. In the temperature range between 17 and 27°C, flowering rate increases almost linearly. Type of cultivar and plant age have an additional effect (De Koning, 1994). Differences of 10 and 20%, respectively, were observed.
If seedling production occurs with a light intensity of 60 µmol m^{-2} s^{-1} and a 16-hour photoperiod, flowering occurs after 50 days (for the cultivar 'Counter'). Subsequent flower trusses occur every 8.7 days (for

Figure 6.18. ***Fruit development time.***
Source: Cockshull et al., 1992. (Reprinted with permission from Headley Brothers.)
The development time (days) from flowering to harvest of the first (circles) and fifth (squares) fruit of each truss for the cultivars 'Calypso' (closed markers) and 'Counter' (open markers). Seeding occurred on October 24, and the crop was terminated on September 1.



trusses 1-6), while an average of 6.8 days is required for the trusses 7-10 (Cockshull et al., 1992). Lighting with HPS lamps increases leaf temperature by a few degrees. Possibly, the rate of flowering is increased as a result of the higher leaf temperature due to the large temperature effect on the time between truss initiation and flowering (De Koning, 1994).

Development period of the fruits

The time period from flowering to harvest mainly depends on temperature. If the first truss flowers in early January, harvest begins on average after 58 days at a daily average temperature of approximately 18°C. This time period is reduced to 46 days after first flowering in June and July (Heuvelink, 1996; De Koning, 1994). The increase in development rate is caused by higher average day and fruit temperatures during the summer. Furthermore, differences are observed for different truss numbers and cultivars (Figure 6.18). The minimum night temperature was 15°C, which explains the relatively long development time. Generally, this development time varies between 40 and 65 days (Ho, 1996). At an average day temperature of 21°C during the winter months in New Jersey, a development time range of 48-51 days was found for the cultivar 'Dombito' (McAvoy et al., 1989).

***Additional comments related to** Figure 6.19.*
See also Figure 6.17.
Top: *Shoot dry mass in gram per plant.*
Middle: *Leaf area in cm^2 per plant.*
Bottom: *Leaf area ratio, i.e., leaf area in cm^2 per mg.*
The cultivar is 'Carmello'. A 17-hour photoperiod was maintained. Supplemental lighting was provided for 15, 11, and 5 hours (corresponding with 58, 41, and 19% of the total light sum), resulting in total light sums of 21.8, 15.8, and 9.3 mol m^{-2} d^{-1}.
*Sowing occurred on December 3 (**I**), January 17 (**II**), and March 8 (**III**). Respacing (pricking out) occurred 15 days after sowing. The letters **a** and **b** shown in the figures indicate that the observed differences are statistically significant.*

Fruit size

There are large variations between types and cultivars. A beefsteak tomato can achieve 450 g, while a cherry tomato has an average fresh mass of only 15 g. In addition, the temperature has a large effect on fruit size, through the development rate and the availability of sugars (see also the section on yield). Fruit growth follows a S-shaped curve. Maximum growth rate is reached after 40% of the time to maturity (De Koning, 1994). This occurs during the period of rapid growth (3 to 5 weeks after fruit set). The uptake rate of assimilates (sugars) is crucial for the ultimate fruit size, and has a positive relationship with the maximum growth rate (Grange et al., 1993). Lighting is therefore most effective during this stage (McAvoy, 1989). However, fruit size can be severely restricted by water stress and/or a high EC of the nutrient solution. In addition, the potential fruit size depends on the position of the truss on the plant, and of the position of the fruit within the truss (De Koning, 1994). The fruit size of the first truss(es) is smaller than that of subsequent trusses. This effect declines as the light level increases. The second, third, and fourth fruit in a truss are the biggest while the last fruits are about 20% smaller. The potential fruit weight at 23°C is about 40% lower than that at 17°C (De Koning, 1994). Fruit size can be effectively managed through truss pruning and the maintaining a certain number of

Figure 6.19. ***The effect of HPS lighting with an intensity of 100 µmol m^{-2} s^{-1} on seedling production started at three different sowing times, (the seedling production is defined as the time between respacing, pricking out, to plants with the first flower truss).***
Three sowing times (I, II, III), lit (hatched bars), unlit (clear bars).
Source: Boivin et al., 1987. (See additional comments in the accompanying text box.)
(Reprinted with permission of American Society of Horticultural Science.)

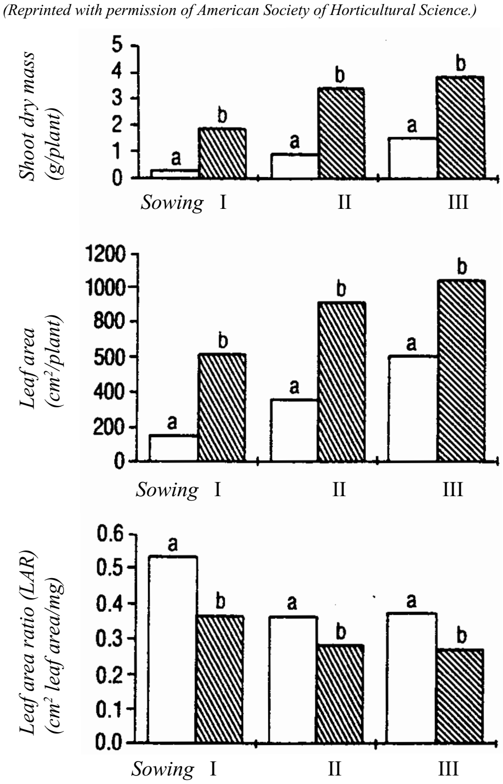


Figure 6.20. ***Relationship between fruit mass and plant/shoot density.*** *Source: Cockshull and Ho, 1995.*
(Reprinted with permission from Headley Brothers.)
The harvest of Class I fruits per 4-week periods at plant densities of 2.04 (squares) or 3.06 (triangles) plants/m². The closed markers and solid lines represent plants without extra side shoots, the open markers and dashed lines represent plants with an additional side shoot added in two stages: in week 9 and in week 14.

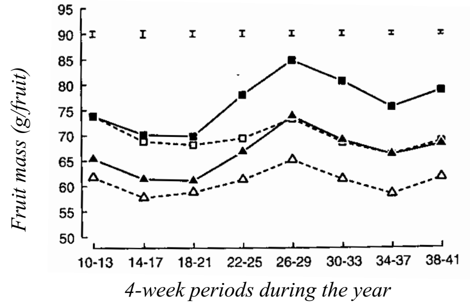
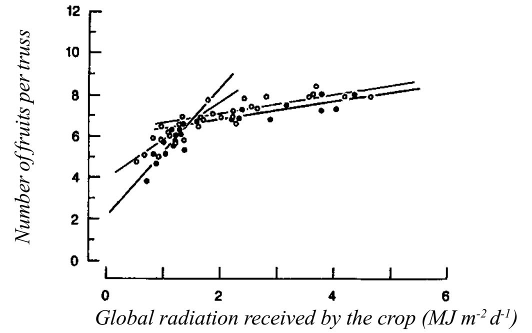


Figure 6.21. ***Relationship between the number of fruits per truss and the amount of global radiation received by the crop.*** *Source: Cockshull et al., 1992.*
(Reprinted with permission from Headley Brothers.)
The average daily global radiation during the period of 6 days before flowering of the first flower truss to 3 days thereafter, for the cultivars 'Calypso' (open circles) and 'Counter' (closed circles).



shoots per square meter. The latter should be adjusted to the amount of available light. In an lighting experiment with the cultivar 'Picolino', the stem density was raised from 3.3 to 3.75 stems per square meter (Visser, 2000). Figure 6.20 shows the results of an experiment in Littlehampton (UK) investigating the effect of stem density on the fruit size.

Two plant densities were used, 2.04 and 3.06 plants per square meter, and the number of shoots per square meter was increased with, on average, 1.01 shoot per square meter (Cockshull and Ho, 1995). The higher stem densities reduced the fruit mass. But starting at a density of 2.04 plants per square meter, an increase of the stem density to 3.06 in weeks 9 and 14 (open square) did not affect fruit mass (approximately 70 g). The effect of increasing the stem density lags 10 weeks behind, because shoot growth occurs in the 10 weeks before harvest. After week 21 (end of May) the fruit mass strongly increased when the stem density was not increased (solid square). If lighting is provided, stem density should be adjusted.

Yield

The yield is determined by the balance between the vegetative and generative growth at a given supply of assimilates (sugars). The ratio between the two is largely determined by the sink of the fruit load, in other words by the total assimilate demand of all fruits. If the latter is high, it results in low vegetative growth, small fruits and increased risk of flower abortion. Figure 6.21 shows the effect of the light sum on the number of fruits per truss during a cropping period from December 18 to early October. Light levels below 1.5 MJ m^{-2} of global outside radiation result in an increased incidence of reduced fruit set, poor flower quality or abortion. This light sum corresponds with 3.1 mol m^{-2} d^{-1}. In The Netherlands during December and January inside the greenhouse, low average light sums occur, of 2.3 and 3.0 mol m^{-2} d^{-1}, respectively. Empirical data indicate that, in The Netherlands, especially during the period from mid-December to mid-January there are difficulties with flowering and fruit set.

The fruit load should be adjusted to the assimilate supply which fluctuates during the course of the year due to the changing amounts of sunlight.

Long term, the fruit load per square meter of greenhouse area can be manipulated through changing the plant or stem density and/or the number of fruits per truss (De Koning, 1994).

Short term, this balance can also be influenced by other factors. Low night temperatures, high EC of the nutrient solution, and water deficit (stress) reduce the vegetative growth. On the other hand, additional light, high day temperatures, and carbon dioxide enrichment stimulate the generative growth (Ho, 1986). The temperature effect is complicated. On the one hand, at high temperatures, the fruits import more sugars and the fruit growth is stimulated as long as there is no water deficit. But on the other hand, if a water deficit develops as a result of increased transpiration, the fruits will expand less. In the long term, high temperatures result in smaller fruits and a quicker maturity of the fruits (De Koning, 1993). Fruit size will only increase at high temperatures if the supply of sugars is not limiting and water stress is avoided (Ho, 1986).

Relationship between light sum and yield

There is a positive relationship between the light sum

Figure 6.22. ***Outside global radiation and the effects of plant densities on marketable yield.*** *Source: Cockshull and Ho, 1995. (Reprinted with permission from Headley Brothers.)*
Global radiation (circles); plant density: 2.04 (squares), 3.06 (triangles) plants/m². Seeding occurred on November 6, transplanting on December 18, and the crop was terminated on September 21.

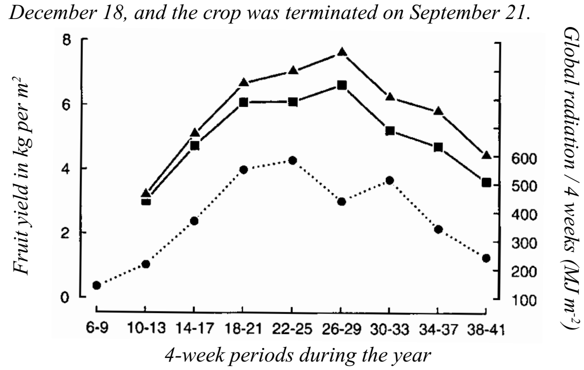
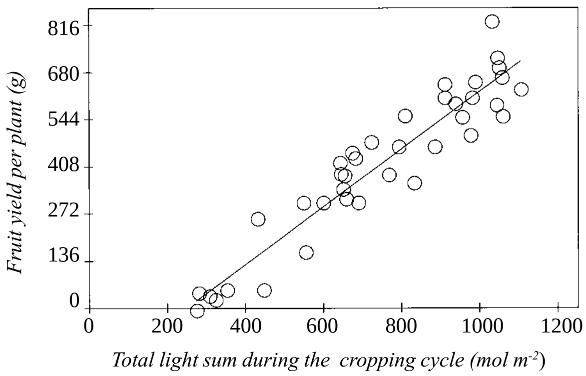


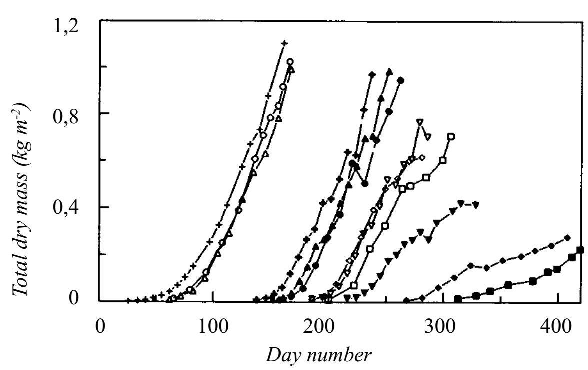
Figure 6.23. ***Relationship between fruit yield (fresh mass) and the total light sum for a tomato crop.***
Source: McAvoy, Janes, 1991.
(Reprinted with permission from Headley Brothers.)
The cropping cycle was only 60 days and included the yield of only one truss. Plant density was 12.3 plants/m^2. The data represent yields obtained both with and without HPS light for all twenty crops.



received by the crop and yield. Therefore, yield reaches a maximum during the summer and declines during the winter months (Figures 6.22 and 6.24). In Figure 6.23, this relationship is expressed as tomato production per plant (fresh mass) and the total light sum in the period October -July, with or without supplemental lighting (Janes and McAvoy, 1991). A positive linear relationship is apparent. These data are based on a short cropping period (60 days) and the yield of one truss ('single cluster tomato system'). After approximately 240 mol m^{-2} fruits start to develop. At the end, after 1,100 mol m^{-2} a truss of about 720 gram is harvested. Flowering and fruit set are not endangered during the cropping periods because total light sums are in the period (October -July) in general higher than 4 mol m^{-2} d^{-1} (Figure 6.26). As indicated earlier, light sums under 3.1 mol m^{-2} d^{-1} increase strongly abortion of flowers and less fruit set (Figure 6.21). Thus, the relationship between production and light sum in Figure 6.23 is very reliable.
For the growth of a truss of 740 gram, 860 mol m^{-2} is needed (1,100-240 mol m^{-2}). This means a tomato yield of 0.84 g fresh mass per mole per plant, or with 12.3 plants per square meter,

10.3 g fresh mass per mol m^{-2}. **(1)**

Figure 6.24. ***Dry matter production (cumulative) related to the time of the year.*** *Source: Heuvelink, 1996.*
Each of the 12 crops (plantings) lasted for about 100 days and four to nine clusters were harvested. The plant density was 2.1 plants m^{-2}. (Day 1 = 1 January)



For a crop, (from November 28 until August 26), in Littlehampton, UK, during the first 14 weeks of harvest (February to May), a tomato yield of 2.01 kg fresh mass per 100 MJ m^{-2} of global radiation inside the greenhouse was obtained (Cockshull et al., 1992). This means: **9.7 gram fresh mass per mol m^{-2}.** **(2)**
During this period, a close relationship was observed between the 14-day yield and the amount of light received during the previous ten weeks, in other words, for this experiment, the average development time of the fruits. After 20 May, 2.65 kg of fresh mass was harvested per 100 MJ m^{-2} of global radiation received by the crop (Cockshull et al., 1992). This means:

12.8 gram fresh mass per mol m^{-2}. **(3)**

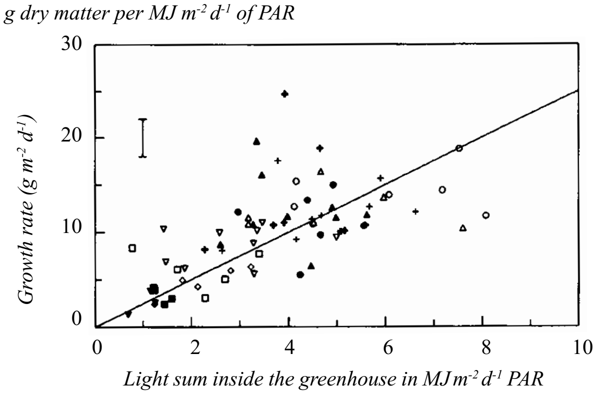
The first figure of Cockshull resembles the results observed previously in a greenhouse operation in The Netherlands: 2.07 kg per 100 MJ m^{-2} (De Koning, 1989), or: **10 gram fresh mass per mol m^{-2}.** **(4)**

In summary (1-4), the relationship between the fresh fruit mass and the light sum was found to range from:

9.7 - 12.8 gram fresh mass per mol m^{-2}.

The British experiments showed further that 1% less light resulted in approximately 1% less yield, at least during the first 14 weeks. The higher the light levels the higher the production (Cockshull et al., 1992).
However, when the light becomes the limiting growth factor, the distribution pattern of assimilates (sugars) in the plant changes (Heuvelink, 1996). The vegetative growth (leaves, stems) gets priority over the generative growth. Well-known symptoms are reduced quality of the flowers, reduced fruit set, abortion of flower and cluster, smaller fruits, and fewer fruits per cluster. The growth rate is reduced as well. These phenomena are shown in Figures 6.24 and 6.25.
Abortion and poor fruit set are also highly dependent on total fruit load. For example, when 7 or 10 clusters remain on the plant simultaneously, the first cluster can almost be harvested while the 7th or 10th cluster starts flowering. The developing fruits have a negative effect on the development of new trusses when the production of assimilates decreases. For

Figure 6.25. ***Crop growth rate related to the light sum received inside the greenhouse for twelve different crops (see also Figure 6.24).*** *Source: Heuvelink, 1996.*
The linear relationship shows a crop efficiency of approximately 2.5 g dry matter per MJ m^{-2} d^{-1} of PAR



example, if the light intensity of 300 μmol m^{-2} s^{-1} is reduced by 30 or 43%, the top three clusters show a poor or very delayed development (providing 30% less light) or do not develop at all (providing 43% less light) (Durieux, 1997). In the first case, the yield is reduced by 30%, while in the second by at least 50%. These experiments showed that a light sum of less than 12 mol m^{-2} d^{-1} (and a 16-hour photoperiod) increased the risk of abortion of flowers/trusses. In The Netherlands, from mid-September to mid-March the ambient light sum inside the greenhouse is less. To a certain extent, a similar trend is shown in Figure 6.21 (6 MJ m^{-2} d^{-1} corresponds with 12.4 mol m^{-2} d^{-1}).
Figure 6.24 shows the significant effect of the light sum on the total dry matter production. Plantings 1 through 5 occurring from January through May showed the highest dry matter accumulation, but the last two plantings, on September 25 and November 8, the lowest. The July-plantings (7 through 9), as well as the tenth (August 3) produced significantly less than those in June. The average daily light sums during the production period correlated well with the total production of the different plantings. The first four clusters of the tenth planting which flowered in August and the first half of September, experienced very little difficulty, but subsequent clusters did (due to lower light levels). For the 11th and 12th plantings, the average dry mass of the first four clusters was about one-half of the previous plantings.

Growth rate

The growth rate of a tomato crop is linearly related with the light sum (Figure 6.25). In the last two weeks of December with a light sum of about 0.5 MJ m^{-2} d^{-1} PAR or 2.3 mol m^{-2} d^{-1}, the growth rate approaches zero, as is shown in Figure 6.24 for the last planting. The curve is then almost horizontal. From Figure 6.23 it can be calculated that a minimum of 4 mol m^{-2} d^{-1} is needed for a positive yield (240 mol m^{-2} /60 days). Any additional light will benefit fruit production. Although this is based on single-truss production, this could apply to normal crops with many trusses. It may explain why lighting with a low intensity, as has been tried in The Netherlands in the past during the winter, has little effect on fruit production. For example, when supplemental lighting is given for 12 hours at a light intensity of 3,400 lux or 40 μmol m^{-2} s^{-1}, an additional light sum of 1.7 mol m^{-2} d^{-1} is realized. This sum, when added to the natural average light sum inside the greenhouse in December (2.3 mol m^{-2} d^{-1} in The Netherlands), provides a total light sum of just 4 mol m^{-2} d^{-1}.

Dry matter distribution

It is important that 54-60% of the dry matter (net photosynthesis) is distributed to the fruits. However, when light becomes limiting, this amount is reduced to 35-38%, as observed during fall plantings (plantings 11 and 12). Fruit set is poor while more dry matter remains in the leaves and stems. When a long cropping period (1-year) is used instead of several shorter ones (Figure 6.24), about 70% of the dry matter is fixed by the fruits in the first cluster (Heuvelink, 1996).

Lighting

As it has been explained earlier, there are few benefits from lighting with 3,000 lux (35 μmol m^{-2} s^{-1} or 7 W m^{-2} PAR). Computer models simulating plant growth confirm this. During the winter months, the dry matter percentage distributed to the fruits is much lower, and, therefore, the additional costs are not compensated for by the (low) additional yield (Van den Berg, 2000). To obtain a better distribution of the dry matter to the fruits, higher light intensities (or sums) are required.
This result was also observed in the US (New Jersey, 40°NL). It was demonstrated that lighting with 150 μmol m^{-2} s^{-1} increased the yield by 90% for a crop with 13 harvested clusters (McAvoy et al., 1984). Planting took place in early January and lighting was applied until mid-March using an 18-hour lighting period and after early April through 1 July an 8-hour period. In early January, this resulted in a total light sum of 10 mol m^{-2} d^{-1}, using a light intensity of 100 μmol m^{-2} s^{-1} (Figure 6.26). The control group reached a yield of almost 9.7 kg m^{-2} while it increased to 15.7, 17.4, and 18.4 kg m^{-2} using light intensities of 100, 125, and 150 μmol m^{-2} s^{-1}, respectively.

Figure 6.26. ***Natural light (solid circles) and natural light supplemented with HPS light (open circles) during the course of the year inside the greenhouse in New Jersey, 40°NL, USA.*** *The light sums are daily means over two week periods. Source: McAvoy, Janes, 1991. (Reprinted with permission from Headley Brothers.)*

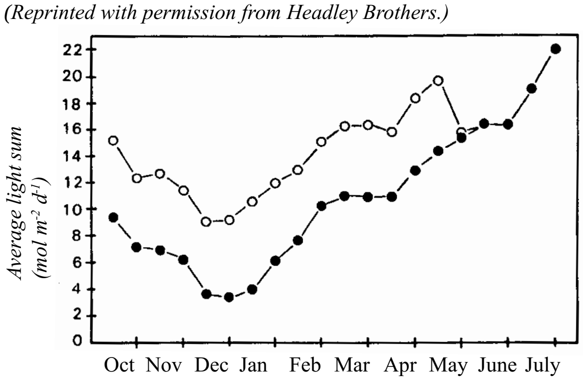
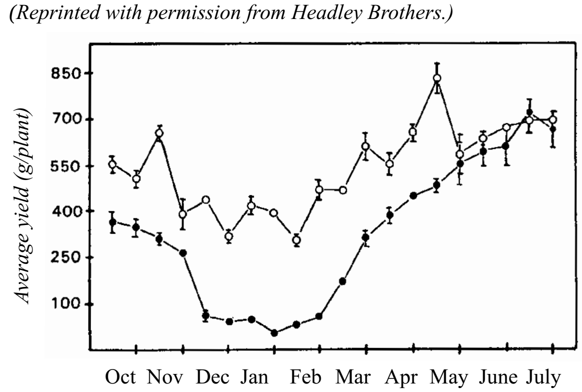


Figure 6.27. ***Comparison of the production of tomato plants grown with (open circles) and without (solid circles) supplementary light, see also Figure 6.26.*** *Source: McAvoy, Janes, 1991. (Reprinted with permission from Headley Brothers.)*



Another experiment was conducted in New Jersey in which tomato plants produced only one cluster by pruning at two leaves above the cluster. One planting took only 60 days. The plant density was 12.3 plants per square meter, with a light intensity of 100 µmol m^{-2} s^{-1} for 18 hours (04:00-22:00 hour) from September 15 through May 15 (McAvoy et al., 1989; Janes and McAvoy, 1991). The light sums inside the greenhouse deviate significantly in winter from those in The Netherlands (4.6 mol m^{-2} d^{-1} in stead of 2.3 mol m^{-2} d^{-1}), see Figure 6.26 and Tables 5.3a/b. A comparison of Figures 6.26 and 6.27 shows that the yield is primarily controlled by the light sum. In mid-December, the production per plant increased from 75 g to 425 g and in mid-January from 70 g to 410 g (a more than 500% increase). Even towards the end of April, the yield increased using lighting from 450 g to 665 g per plant (a 48% increase).

Experiments in Québec (47°NL), using a light intensity of 150 and 300 µmol m^{-2} s^{-1} showed a strong benefit on early yield (Tremblay et al., 1984). Eighty-five days after transplanting, the yield using the lower intensity was 3 kg m^{-2}, while with the higher intensity it was 7 kg m^{-2} and no fruits had been harvested of the control plants. Although the largest yield increase was obtained using a light intensity of 200 µmol m^{-2} s^{-1}, it has been calculated that the largest economic returns are obtained with light intensities between 100 and 150 µmol m^{-2} s^{-1}, depending on the location in Canada. Vancouver, Canada is at 50°NL, while Naaldwijk, The Netherlands is at 52°NL. Average global radiation in Vancouver in December is 2.28 MJ $m^{-2}d^{-1}$, while in Naaldwijk it is 1.82 MJ m^{-2} d^{-1}. Other cities such as Toronto and Montreal receive during that month 3.9 MJ m^{-2} d^{-1} (Ehret, 1989). Therefore, in comparison for The Netherlands, a supplemental light intensity of 150 µmol m^{-2} s^{-1} would be preferred rather than 100 µmol m^{-2} s^{-1}. Obviously the economics are totally different in The Netherlands, so that this intensity is only an estimate.

At the Research Station in Naaldwijk, year-round production was evaluated using a computer program for a cropping system with suspended gutters and supplemental lighting when the outside radiation dropped below 300 W m^{-2}. The plants received a 4-hour dark period every day, and the carbon dioxide concentration was maintained at 1,000 ppm when the ventilation windows were closed and at 360 ppm when the vents were open. Supplemental lighting was provided using light intensities of 10, 15, and 20 klx (or 118, 176, and 235 µmol m^{-2} s^{-1}). These treatments were compared with an unlit control crop planted in week 48. The year-round yield was significantly increased due to the use of supplemental lighting (Table 6.18). In addition to the positive effects of lighting, production continued during the winter. For the control treatment, there was no production for three months.

Using a light intensity of 10 klx during the winter, a production of 0.8 kg m^{-2} per week was realized compared to 2.4 kg m^{-2} during the summer. The results with a light intensity of 20 klx were 1.2 and 2.8 kg m^{-2} wk^{-1}, respectively. Generally, these numbers correspond well with lighting effects on the dry mass and fresh fruit mass as described above.

Table 6.18. ***Lighting and production of tomato.***
Source: Van den Berg, 2000.

Lighting *lux*	*or µmol $m^{-2}s^{-1}$*	**Yield** *kg m^{-2} jr^{-1}*	**Increase** *%*	**Remarks** *cropping period*
-	-	55	-	Week 48 - 45
10,000	**118**	92	67	Yearround
15,000	**176**	106	93	Yearround
20,000	**235**	118	115	Yearround

Figure 6.25 shows that approximately 2.5 g of dry matter is produced per MJ of PAR received for a soil-grown crop without carbon dioxide enrichment. Using current growing methods with substrates and optimum climate conditions, a value of 3.5 g per MJ of PAR is possible (Heuvelink). Consequently, when for example 60% of the dry matter produced is used by the fruits during the winter, 2.1 g per MJ of PAR is available for fruit production. The dry matter content of tomato during the winter is approximately 5% (in June-July it is approximately 6%, De Koning, 1993). As a result, during the winter, a daily increase of 42 g of fruit (fresh mass) per MJ of PAR can be expected. If 1 MJ m^{-2} d^{-1} of PAR equals 4.6 mol m^{-2} d^{-1}, there is a daily increase of 9.1 g fresh mass per mol of supplemental lighting.

According to Dutch practices, supplemental lighting is provided when outside global radiation drops below 300 W m^{-2}. The data shown in Appendix 1 indicate that, using this set point, continuous supplemental lighting should be applied from October through February using a maximum 20-hour photoperiod. In The Netherlands, during December, the average natural light sum inside the greenhouse is 0.5 MJ m^{-2} d^{-1} of PAR or 2.3 mol m^{-2} d^{-1}. Supplemental lighting using a light intensity of 118 µmol m^{-2} s^{-1} and a 20-hour photoperiod results in an additional light sum of 8.5 mol m^{-2} d^{-1}. Therefore, the total light sum in December reaches 8.5 + 2.3 = 10.8 mol m^{-2} d^{-1}, resulting in a fresh fruit mass production of:

10.8 mol m^{-2} d^{-1} x 9.1 g mol^{-1} x 7 d wk^{-1} = 688 g m^{-2} per week.

Cockshull (1992) reached a different relationship (see the section on the relationship light sum and yield): 9.7 g per mole (Feb-May), resulting in a fresh fruit mass production of:

10.8 mol m^{-2} d^{-1} x 9.70 g mol^{-1} x 7 d wk^{-1} = 733 g m^{-2} per week.

Computer simulations performed by the Dutch research station resulted in a fresh fruit mass production of:

800 g m^{-2} per week or 10.5 g per mole.

In comparison with the previous two calculations, the result from the computer model is rather high because all growth factors have been optimized.

Photoperiod

With photoperiods of more than 17 hours, the incidence of chlorosis, disorders, reduced growth and production increased (Demers et al., 1998). Even if the 7-hour dark period is divided into two short dark periods of 3.5 hours, chlorosis can occur (Vézina et al., 1991). For many cultivars, a dark period of less than 4 hours is known to be harmful (Bradley et al., 1985; Logendra et al., 1990; Vézina et al., 1991; Dorais et al., 1996). In The Netherlands, providing 6 to 8 hours of darkness is common practice (Germing, 1963; Klapwijk, 1986), in North America 7-10 hours (Demers et al., 1998).

Recent research results indicated that a photoperiod of 14 hours is optimum for growth and yield of the cultivar 'Trend' (Demers et al., 1998). However, it was also observed that growth with 24-hour lighting during the first 5-7 weeks of the production period was better than with 14 hours of lighting. After this period, the growth declined rapidly under continuous lighting so that at the end of the harvest the total production was higher using the 14-hour photoperiod. This suggests that a 20-hour photoperiod or longer can be provided at least during the first 5 weeks of the production period (immediately after transplanting). Whether these Canadian results can be applied globally is unknown.

Chlorosis is caused by the accumulation of starch and sugars in the mesophyll cells, adversely affecting photosynthesis. The number of fruits on the plant did not influence this accumulation (Demers et al., 1998). However, tomato production close to the Northern Circle during the summer did not show any signs of chlorosis even when using HPS lighting.

HPS light effects on plant shape

The special color spectrum of HPS lamps influences the shape of tomato plants. This has been investigated for each color (Mortensen et al., 1987). Green and yellow light, which represent about 40% of HPS light (Table 7.2), considerably promote internode length and leaf area when compared to natural light. The leaves have a lower specific leaf area (g m^{-2} of leaf area). Red light (650-700 nm) causes the same effects, but to a lesser extent compared to green and yellow light. These qualitative effects are beneficial during the winter for photosynthesis and light penetration in the crop. Research from Québec, 47°NL, pointed out that when lighting is provided using a light intensity of 100 µmol m^{-2} s^{-1} and a 17-hour photoperiod during seedling production (from respacing, pricking out, until the development of the first cluster), the dry mass, leaf area and mass per unit of leaf area increased (Figure 6.19; Boivin et al., 1987).

Lighting improves the production of chlorophyll and leaves. Plants that have been lit during the seedling stage will be able to take more advantage from additional lighting after transplanting. In Figure 6.19 the effect of lighting with an intensity of 100 µmol m^{-2} s^{-1} during seedling production is shown. When transplanting into the greenhouse occurs at the end of January, the first harvest follows in early April. Subsequently, the lit plants stay ahead of the unlit plants, in terms of yield (Figure 6.17).

Flavor

Besides an increase in yield, the flavor is improved as well due to increased lighting. Flavor is determined by the concentrations of sugars and acids. The sugar concentration in the fruit sap increased from 1.8 to 2.8 g per 100 ml when the light sum increased from 5 to 15 MJ m^{-2} d^{-1} (Hobson et al., 1971). Converted to PAR inside the greenhouse, these light sums are 6.2 to 18.6 mol m^{-2} d^{-1}.

Experiment at a commercial tomato grower

In The Netherlands, an experiment at a commercial tomato grower was conducted with a light intensity of 10 klx or one 600-watt lamp per 7 m^2 of greenhouse floor area. The lamps were turned on when the outside light intensity dropped below 20 klx. Supplemental lighting was provided using a maximum 16-hour photoperiod. Using a 4-m high greenhouse, growing was done in gutters, which were suspended at a height of 60-70 cm, rather than 120 cm. This made crop management activities easier and the growing point could be removed easier.

In this experiment, three plants were planted per 60 cm bag of coco coir. Plantings took place on around mid-August and mid-February. Young plants were planted between older plants to prevent immediate exposure to the full light. As a result of lighting, the leaves remained smaller and the plants were more compact. Plant density was increased from 3.3 to 3.75 plants per square meter, which resulted in a higher production and a 15-20% higher fruit mass. A standard (unlit) crop with the cultivar 'Picolino' yielded 32 kg m^{-2} and required 65 m^3 of natural gas per m^2, or 2.03 m^3 per kg. With supplemental lighting, a yield of 50.4 kg m^{-2} was achieved using 88 m^3 of natural gas (including lighting). This corresponds with 1.75 m^3 of natural gas per kg of fruit, which is a 16% decrease in energy input. This decrease is caused by the fact that the lamps emit a significant amount of heat. The high heating pipe (positioned near the top of the canopy) is no longer necessary. The 24-hour average temperature is about 2 degrees higher than the normally maintained temperature. The target CO_2 concentration was maintained at 1,200 ppm. According to a computer model, the cultivar 'Voyager' grown with supplemental lighting can produce a yield of 88.5 kg/m^2 (Visser, 2000; Anon., 2000; Guiking, 2000).

Advantages of lighting (for production in The Netherlands)

Lighting of a tomato crop during the production phase has many benefits:

- Year-round production is feasible;
- Higher production and better and more constant quality; *e.g.* the cultivar 'Picolino' grown with supplemental lighting produced a better quality compared to a comparable product grown in Spain or in other countries;
- Labor requirements are more constant throughout the year;
- Production during the winter results in higher prices;
- Uniform yield throughout the year leads to a bet-

ter marketing position, so that sale arrangements for the whole year can be made more easily with regular buyers
- Even the last clusters are of a better quality;
- During the winter, the tomatoes maintain a better flavor due to a higher sugar content; it is possible to guarantee buyers year-round a minimum sugar content, *e.g.* based on the brix-number;
- Competitive position with respect to Southern Europe is better, both from the point of view of costs and of quality;
- Translocation of the greenhouse operation to, for example, Spain, is no longer necessary; growing conditions and marketing can be better controlled in The Netherlands;
- 'Tracking and tracing', which is gaining importance, is guaranteed. Throughout the year, it is easier to determined where the produce came from and under what conditions it was grown; for imported produce this is much more difficult;
- Since the production takes place only in The Netherlands, consumer loyalty can be increased. Transportation costs are lower.

Recommendations

It is recommended to adjust the lighting regime during seedling production to that during fruit production in order to optimize the transition to the production greenhouse. Illuminated plants are heavier, have thicker and bigger leaves, which are adapted to more light. Lighting reduces the incidence of flower abortion in the first cluster.

Lighting can be applied throughout the year because, even during the summer, crop photosynthesis is not yet saturated in Dutch greenhouses. During the period from September to mid-March, the natural light sums are lower than 12 mol m^{-2} d^{-1}, resulting in a strong reduction in yield and quality. In order to maintain high(er) light sum, supplemental lighting should be provided. During December and January, a light intensity of 175 µmol m^{-2} s^{-1} is needed (almost 15 klx) with a lighting period of 16 hours. During the winter months, this results in an average weekly production of 1 kg m^{-2} (Dorais et al., 1991).

As a tomato crop receives more light, the fruit load per plant may increase as well. This also results into more transport of sugars to the fruits.

The maximal photoperiod for tomato is 20 hours for no more than 5-7 weeks. This allows for the application of more light during the season with the lowest light levels. Nevertheless, caution is required. In The Netherlands, frequently 16-18 hours of lighting and in Canada 14-17 hours of lighting are provided. The optimum photoperiod for the cultivar 'Trend ' is 14 hours. It still has to be determined whether this photoperiod can be successfully applied to other cultivars and types as well.

Flower abortion is more pronounced when the light sum drops below 3.1 mol m^{-2} d^{-1}

Before fruit development is possible, the production of sugars should be higher than the consumption through respiration. This occurs at light sum above 2-4 mol m^{-2} d^{-1}, depending on the cultivation technique. Above these light sums, the fruit yield is directly proportional to the light sum. During the winter, every additional mol m^{-2} d^{-1} can result into an increase in production of 9.1 - 10.5 g fresh fruit mass per square meter per day, or even higher after mid-May: 12.8 g. When the market price of tomatoes is known, an exact calculation can be made determining which light intensity is most profitable, balancing additional yields with additional costs for lighting.

If supplemental lighting is provided using a light intensity of 10 klx or 118 µmol m^{-2} s^{-1}, an annual fruit production of 92 kg per square meter is possible, based on estimates by the Dutch research station. This is an increase of 67% compared to current Dutch production methods (for example, using a high wire system and single planting in week 48).

The more light a tomato crop receives, the higher the yield and the better the quality will be. Fruit size is closely related to the quantity of available sugars. The number of fruits per cluster and the stem density per square meter should be adjusted to the light sum so that optimal production can be achieved. Climate control should be adjusted to the lighting method.

Table 6.19. ***Summary of light intensities and photoperiods for year-round production of greenhouse vegetables.***

Column 1: *Light requirement (vh = very high: > 30 mol m^{-2} d^{-1}).*
Column 2: *Desired light intensity for year-round production.*
Column 3: *Maximum photoperiod*
Column 4: *Minimum light sum. (**MLS**). Below this level problems increase significantly, for example, delay in growth and development (**A**), and flower abortion (**B**).*
** Below 12-13 mol m^{-2} d^{-1} growing periods increase very fast.*
At about 2 mol m^{-2} d^{-1} growth rate is zero, depending on circumstances.

	1	2	3	4 A	4 B
	Light requirement	**Intensity** *µmol m^{-2} s^{-1}*	**Photoperiod** *hour*	**MLS** *mol m^{-2} d^{-1}*	
Cucumber	vh	150	18-20	12	-
Eggplant	vh	150	20	12	-
Lettuce	vh	150	13-18	12*	-
Sweet pepper	vh	150	20	12	-
Tomato	vh	175	16-18	12	3.1

7 *Light Sources*

Introduction

The light source is one of the key components of a lighting system. In the following sections, an overview is presented of the light sources available for use in plant production (see also Figure 7.1).

7.1 Incandescent lamps

An incandescent (INC) lamp emits light when an electric current passes through a tungsten filament. As a result, the filament glows and emits light. Measurements show that only 6.7% of the electrical energy input is converted into PAR (the waveband between 400 and 700 nm), and, thus, can be used for photosynthesis (see Figure 3.7 for spectral energy distribution). The rest of the electric energy is converted into heat. Due to this low conversion efficiency, INC lamps are not used for assimilation lighting (Figure 7.2). A 150 W-INC lamp produces 15 lumen per watt, or a total of 2,250 lumen, compared to 150 lumen per watt for a modern 600 W-high-pressure sodium lamp. Although the conversion efficiency of INC lamps has been improved by using special fill gases and filament materials, INC lamps are not near as efficient as discharge lamps (Table 7.1). Therefore, INC lamps are used only for photoperiod lighting, and mostly for short duration, cyclic lighting. Because the long-day effect for many crops can be achieved using discharge lamps instead, INC lamps are frequently no longer used by greenhouse operations equipped with supplemental lighting systems.

Figure 7.2. Electric energy conversion of a 150 W incandescent lamp.

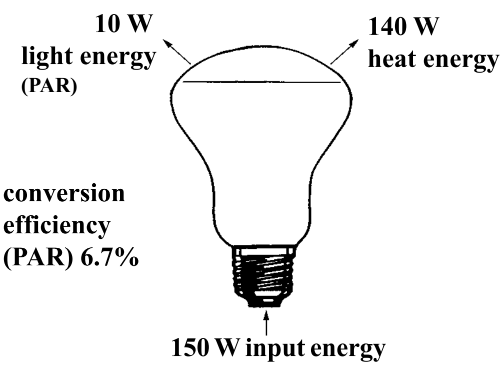
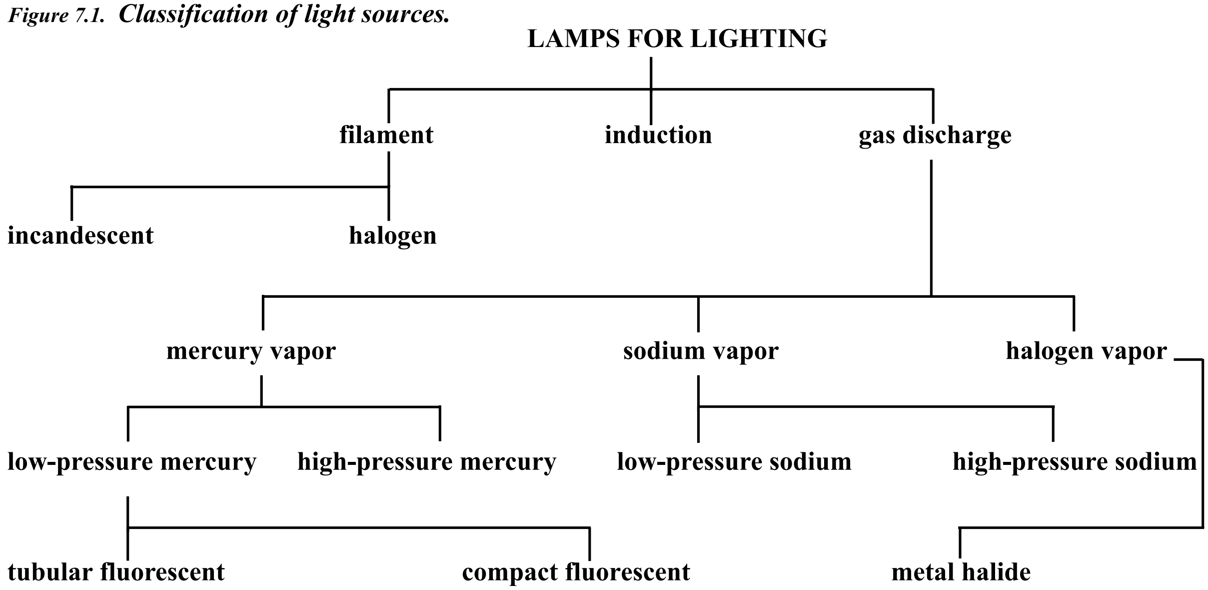


Figure 7.1. Classification of light sources.



7.2 Discharge lamps

Categories

1. Low-pressure
- a. mercury vapor or fluorescent lamps: FL (*e.g. Cool White, Warm White, Daylight*)
- b. sodium vapor lamps: LPS *(e.g. SOX)*

2. High-Intensity-Discharge (high-pressure)
- a. mercury vapor lamps *(e.g. HPL, HR400)*
- b. metal halide lamps: MH *(e.g. HPI-T, HQIT, MVR400, Metalarc)*
- c. sodium vapor lamps: HPS *(e.g. SON-T Plus, Lucalox, Lumalux)*

Because of the low efficiency of INC lamp, research focused on a search for more efficient light sources. In the earlier part of the 20th century, when it became possible to generate higher line voltages, the so-called discharge lamps were developed. The high-pressure sodium lamp was invented in 1931. All discharge lamps consist of a transparent discharge tube made of glass, quartz or sintered aluminum oxide (Figure 7.7), filled with a gas mixture (*e.g.* argon) and a quantity of one or more metals such as sodium, mercury, or halogens. These compounds are vaporized when the arc is brought to the proper operating temperature by passing an electrical current. An electrode is fused to each end of the arc to allow an electrical current to pass. The principle of light generation is in fact the same as for the incandescent lamp: an electric current makes a conductor (in this case a mixture of gas and metal vapor) glow, resulting in the emission of light and heat. In addition to the arc, a ballast and starter are needed to provide a high voltage to ionize the gas (see Chapter 9 for more information).

Discharge lamps are more energy efficient than INC lamps. High-pressure sodium (HPS) lamps, for example, convert about 25 to 30% (depending on the type) of the electric energy into PAR light. In addition, HPS lamps have a much longer lifespan (Table 7.1). The combination of these characteristics makes HPS lamps particularly suitable for supplemental lighting applications.

However, discharge lamps have the undesirable characteristic that their internal resistance drops after the lamp is ignited. Therefore, a current regulating device (ballast) is required to limit the current through the lamp so as not to let it fail prematurely. Although adding the various components to a light fixture increases the cost, as well as increases energy losses, discharge lamps, due to their otherwise favorable characteristics, are the most economical light sources.

As a result of the variation in pressure, composition of the gas, and addition of different metals, a variety of lamp types have been developed. The most important discharge lamps for plant production are described below:

- Fluorescent lamps (FL),
- Metal halide lamps (MH),
- Sodium vapor lamps (HPS).

7.2.1 Fluorescent lamps (FL)

FL lamps are available in a wide range of light colors and color rendering indices (Section 3.1). Frequently, in growth rooms (Figure 7.4), FL lamps are used which approach the daylight spectrum, for example:

- TL-D 58 W/33 with color representation index 63
- TL-D 50 W/830 HF
- TL-D 58 W/840 and TL-5 35 W/840 HE, the latter with an index of 85.

For these FL lamps, about 58% of the PAR energy (400-700 nm) is in the blue/green waveband (400-565 nm).

Figure 7.4 shows the light spectrum of two FL lamps. For both lamps, the light energy peaks occur in the 400-700 nm waveband, and occasionally in the form

Figure 7.3: ***A tissue culture room equipped with TL-D 50 W HF-lamps,*** *(color index 83(0), see Figure 3.10)*.
Source: Philips, 1996.

Figure 7.4. ***Spectral energy distribution of 2 FL lamps. Top: TL-D 58 W/33*** *(light color 4,200 K, see Figure 3.9)*, ***Bottom: TL-5 35 W/840 HE*** *(light color 4,000 K) (Philips).*

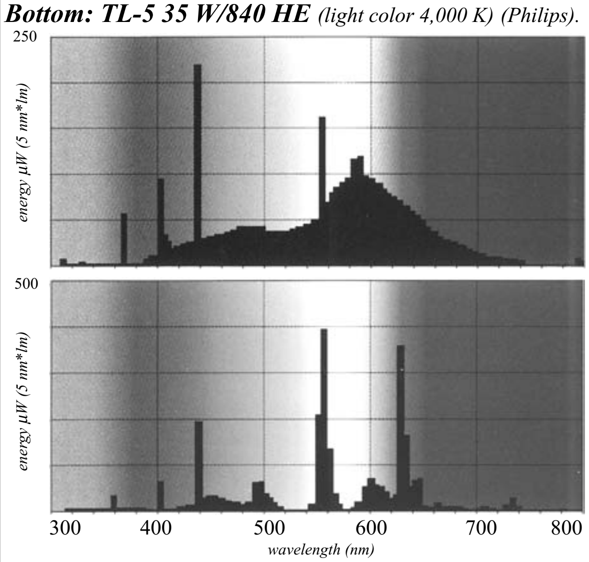


Figure 7.5. ***Spectral energy distribution of a 400 W MH HPI-T lamp.*** *Source: Philips, 1996.*

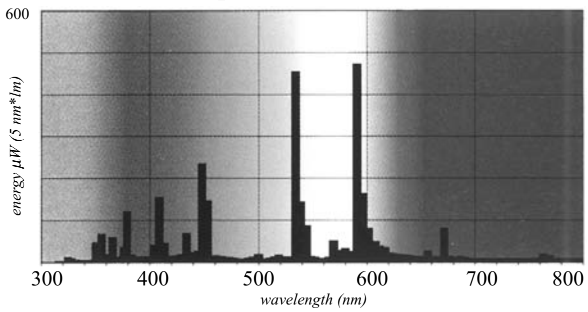
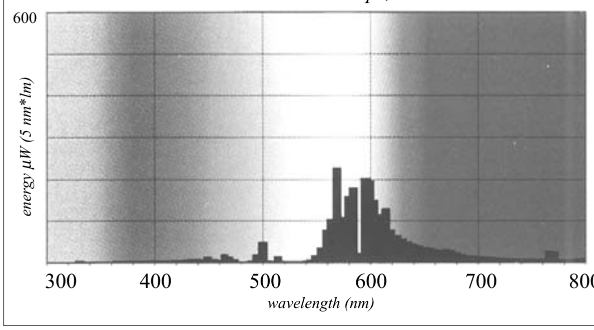


Figure 7.6. ***Spectral energy distribution of a 400 W HPS SON-T Plus.*** *Source: Philips, 1996.*



of a continuous spectrum, as with TL 58 W/33. Compounds such as zinc orthosilicate (Zn_2SiO_4) or magnesium wolframite ($MgWO_4$) convert UV-C radiation (253 nm) of mercury into visible light. For supplemental lighting in greenhouses, the light intensity provided by FL lamps is insufficient. Furthermore, the large fixtures create much shade in the greenhouse, which adversely affects plant growth. Nevertheless, there are many applications for which these drawbacks are less relevant. FL lamps can be used in growth rooms both for photoperiod lighting and for assimilation lighting, *e.g.* in phytotrons, rooms for forcing bulbs, tissue culture rooms, and germination rooms (multi-layer systems). The surface temperature of the FL lamp bulbs is low so they can be mounted close to the crop. Furthermore, it is possible to manipulate the light intensity by using dimmable ballasts, an option that can be used for other lamp types as well. Using such ballasts, the light intensity can be adjusted to match the development stage of the plants. However, not all types of FL lamps are dimmable.

7.2.2 Metal halide lamps (MH)

MH lamps produce a whitish light that closely resembles the spectrum of daylight. Therefore, it seems obvious that, particularly during the early days of commercial supplemental lighting, there was much interest in this lamp type. However, it was soon discovered that, the energy efficiency of MH lamps was not high enough. This is demonstrated in Table 7.1 by the PAR yield (μmol/luminaire watt). In addition, the useful lifespan of MH lamps is not as long as for HPS lamps and the light output during lamp life drops relatively quickly. When using MH lamps, designers often recommend installing 25% more lamps to overcome this steep drop in light output. For particular applications however, for which a more complete light spectrum is required, MH lamps remain a good choice (*e.g.* for growth rooms requiring high intensities).

About 55% of the light energy of a 400 W MH lamp falls in the waveband of 400-565 nm. The highest radiant energy peaks fall in green and orange wavebands (in the 495-565 nm and 590-625 nm wavebands, respectively; Figure 7.5). MH lamps have a wider spectrum than mercury or sodium lamps, because they contain metal salts of halogens. These halogens include fluorine, chlorine, bromine and iodine. Compared to lighting with FL tubes, fewer luminaires are needed when using MH lamps. This can be a clear advantage.

7.2.3 High-pressure sodium lamps (HPS)

The HPS lamp is the most energy efficient lamp for supplemental lighting (Figure 7.6). About 30% of the electric energy input is converted into PAR (400–700 nm; Figure 7.7). Only 14% of the light energy is in the waveband between 400 and 565 nm, most of the rest in the region up to 700 nm. An example is the 400 W SON-T Plus, which has two high-radiant energy peaks in yellow and orange, in 565-590 nm and 590-625 nm, respectively, caused by the sodium vapor.

The high-energy efficiency is demonstrated in Table 7.1 by the PAR yield (μmol/luminaire watt). In addition, the useful life of HPS lamps is twice that for MH lamps. The light output during lamp life will drop less than 10% (Figure 7.9). Despite the poor color rendition, the use of HPS lamps results in excellent plant growth and development, provided the plants receive enough additional natural light. Due to the high surface temperature of the lamp bulb (max. 450ºC), the distance between the lamps and the plants should be sufficient to avoid plant damage.

The newer 600 W HPS lamps have a higher PAR yield compared to the 400 W lamps (Table 7.1). This is possibly caused by a considerable shift of the radiant en-

Figure 7.7. ***Energy conversion for a 600 watt high-pressure sodium lamp.***
A = Arc
B = Ballast

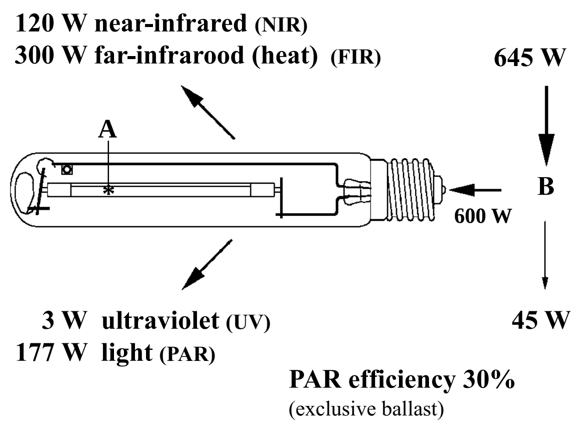


Table 7.1. ***Characteristics of various lamp types, which are used for both supplemental and photoperiodic lighting.***
Sources: manufacturers, Hendriks et al., 1993 (technical modifications excluded).

1 Lamp	2 Manu- facturer *	3 Power excl/incl ballast W	4 Light flux lumen	5 Light efficiency lm/W**	6 Ratio PAR/light fl mW/lm	7 PAR flux mW PAR	8 Radiant yield mW/W***	9 PPF yield µmol/W***	10 Useful life hours
SON-T Plus 400 W	Ph	400/445	55,000	138/124	2.3	126,500	290	1.4	10,000
SON-T Plus 600 W	Ph	600/645	90,000	150/140	2.5	222,260	370	1.6	10,000
SON-T Agro 400 W	Ph	400/445	55,000	138/124	2.5	137,500	309		10,000
NAV-T Super 400 W 4Y	Os	400/445	55,500	139/124	2.3	126,500	290	1.45	10,000
NAV-T Super 600 W 4Y	Os	600/645	90,000	150/140					10,000
Lucalox HO 400W	Ge	400/445	56,000	140/126					10,000
Lucalox HO 600W	Ge	600/645	90,000	150/140					10,000
HPI-T 400 W	Ph	400/445	35,000	88/79	2.8	88,200	198	0.9	±5,000
HQI-T 400/D	Os	400/445	33,000	83/74	2.8	92,400	208	0.9	±5,000
HPL-N 400 W	Ph	400/445	22,000	55/49	2.9				
TL-D 58 W 83	Ph	58/70	5,200	90/74	2.9	15,080	215	1.0	7,500
TL5 35 W/ 830 HE	Ph	35/40	3,650	104/91	2.9	10,585	265		
PLE 20 W	Ph	20/-							
Incandescent 150 W	Ph	150/-	2,060	14/-	4.4	9,750	65	0.3	
Flower Power 100 W	Ph	100/-	1,094	11/-					

* *Ph = Philips, Os = Sylvania/Osram, Ge= General Electric,* ** *excluding/including ballst,* *** *capacity (W) including ballast*

ergy from orange to red (Table 5.2). For the same light intensity, fewer 600 W-luminaires are needed, so that investment and energy costs are lower and the shadow effect is reduced.

Other technical data for the 600 W-lamp include: color temperature 2,000 K, minimum voltage for ignition 198 V, lamp voltage 110 V, lamp current 6.2 A, warm-up period 5 min.

7.3 Lamp characteristics

Additional remarks accompanying the list in Table 7.1:

Column 1: Lamp types

From top to bottom, the list contains three lamp types:

- High-pressure sodium
- Metal halide
- High-pressure mercury
- Fluorescent (low-pressure mercury)
- Incandescent

All these lamp types can be used for photoperiodic lighting. The particular application is, however, crop-specific. Incandescent and the compact fluorescent lamps are used exclusively for daylength extension, while discharge lamps are mostly used for assimilative lighting. Using the energy efficient compact fluorescent lamp (PLE 20W or SLR 18W) and an intensity of 110 lux (1.4 µmol m^{-2} s^{-1}), only one lamp per 9.6 m^{-2} is needed at a mounting height of at least 2 m above the crop .

Mercury vapor and metal halide lamps limit stem elongation because of the larger portion of blue/violet light in their spectrum. FL lamps are frequently installed in growth rooms, tissue culture labs, and germination rooms.

Assimilation lighting can be done with light sources having a different spectral light distribution compared to sunlight. During the day, plants receive enough radiation containing violet and blue light. Although lamps can be designed to have the same spectrum as sunlight, the efficiency of such lamps is usually lower. In growth rooms without sunlight, a complete light spectrum is needed for balanced plant growth. Therefore, the use of FL lamps or a combination of HPS and MH (2:1) is often used for this purpose.

Column 2. Manufacturers

Note that the HPS lamps listed in the table have approximately the same specifications.

Column 3. Power, wattage

Column 3 shows the power consumption of the luminaires, with or without ballast (VSA). With the exception of the incandescent and the compact fluorescent lamps, ballasts are required to operate the lamps. For example, a 400 W SON-T Plus luminaire requires a total energy input of 445 W including the ballast.

Column 4: Light flux

An important characteristic of lamps is thei r luminous flux expressed in lumen (Chapter 5). As lamp wattage increases, so does the luminous flux. As a result, fewer luminaires have to be installed for the same overall luminous flux, or more installed lumi-

Table 7.2. ***Energy distribution (mW) in % for the SON-T Plus 400 and 600 W*** *in the PAR waveband (400-700 nm). Source: Philips, 2000.*

	400 watt	**600 watt**
400-435 nm violet	1.5	1.1
435-495 nm blue	4.5	3.5
495-565 nm green	7.8	8.9
565-590 nm yellow	31.5	32.4
590-625 nm orange	40.2	37.0
625-700 nm red	14.5	17.1
	100.0	100.0

naires will result in higher light intensities, an industry trend experienced during recent years. A drawback of using lumen is that this unit does not directly relate to plant photosynthesis. In fact, lumen should be converted into watts (milliwatts, mW), or preferably into μmol. It is even better to measure PAR radiation directly in these units, because the conversion is usually an approximation. Schurer (1997) advised against the use of conversion factors. However, lamp manufacturers still use lumen as an industry-wide standard.

Column 5: Light efficiency

The light efficiency is expressed in lumen per watt. The energy consumption by the ballast can be either included or excluded. As the table shows, there are large differences among the different lamp types. The 600 W HPS lamp shows the highest efficiency. For these calculations, the decreasing light flux during the useful lamp life should be taken into account (Figure 7.9).

Column 6: PAR energy flux divided by the lamp light flux

The PAR-energy flux (expressed mW) is expressed per unit of lamp light flux, mW/lumen. Using this conversion factor, lumen can be converted into mW of PAR, or lux into mW m^{-2} PAR. An 150 W INC lamp produces a light flux of 2,250 lumen and 9,750 mW PAR. The ratio of 9,750 over 2,250 results in a conversion factor of 4.3 mW (PAR) per lumen. For sunlight, this factor is about 4. Discharge lamps have significantly lower values.

Column 7: PAR flux

PAR flux is used to represent the energy content in the PAR waveband. The units are joule s^{-1}, watt, or milliwatt.

Column 8: Radiant yield

The radiant yield indicates the PAR flux (mW) per watt of electricity (including ballast) input: mW/W. This number is consequently more important than the ratio listed in Column 6 (mW/lumen). The high-pressure sodium lamp has the highest radiant yield.

Column 9: PPF yield

Like in Column 8, this factor indicates the ratio between output and input, but this time as the ratio of the photon flux density in the PAR waveband and the required electric energy: μmol per watt (including ballast). The PPF yield is obtained from Table 5.2, which shows the relationship between μmol and watt of PAR. A 600 W HPS lamp delivers a PAR of 1,084 μmol s^{-1} (Van Rijssel, 1999).

Column 10: Operating hours

The number of operating hours is an important lamp characteristic. The energy efficiency of the lamps declines in proportion to the number of operating hours. Lamp manufacturers usually define the expected lifespan of a lamp in two ways:

A. Useful lifespan

The useful lifespan is the number of hours during which the lamp emits a light flux that is greater than or equal to a predetermined percentage of the average light flux of new lamps. The initial light flux is determined by the manufacturer, and is based on the lamps operating at a certain (nominal) voltage (*e.g.* 230 V in Europe). The effect of line voltage on lamp performance is shown in Figure 7.8. Lowering the line voltage to 210 V reduces the light flux with more than 30%, while a rise to 250 V increases the light sum with more than 30%.

Incandescent lamps have a useful lifespan defined by the time when their light flux reaches 85% of the initial light flux; for discharge lamps this number is 70%.

For SON-T lamps this percentage is 90% after 10,000 burning hours (Figure 7.9). Column 10 shows values for the useful lifespan. Excess voltage always reduces the useful lifespan of the lamp and leads to a strongly declining light yield. It is advisable to consult the lamp manufacturers for specific technical specifications.

Figure 7.8. ***Effect of line voltage on SON-T lamps (HPS)****. Source: Philips, 2000.*

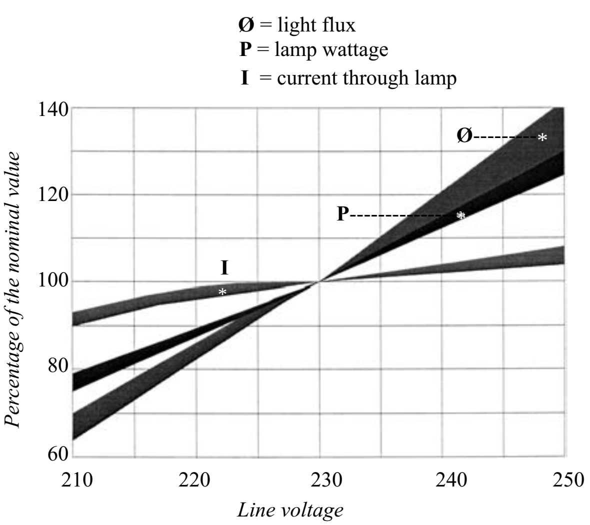
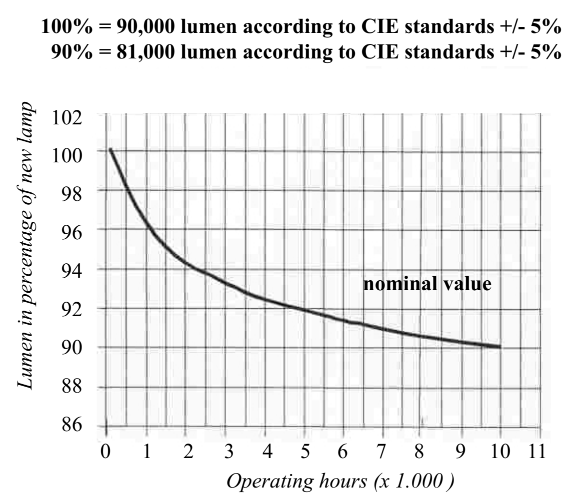


Figure 7.9. ***Relationship between operating hours and light output (lm) for a SON-T Plus 600 W lamp.***
Source Philips, 2000.



B. Average lifespan

The average lifespan is defined as the time after which 50% of a randomly chosen batch of lamps fails. Manufactures frequently use this number (and not the useful lifespan) to indicate the expected life of a particular lamp.

Effective light flux

In reality, the efficiency of lamps is lower than the values presented in Table 7.1. Because it is impossible for the entire light flux to reach the crop, the concept of an effective light flux is introduced. For crop production, incandescent and compact fluorescent lamps are usually placed in fixtures without optics or reflector. As a result, the effective light flux may be considerably less that predicted from laboratory tests. For a free-suspended (no reflector) incandescent lamp used for photoperiodic lighting, the effective light flux is only 40% of the theoretical value. For fluorescent lamps used in growth rooms with white painted walls, and with reflective ceilings and walls, the effective light flux is 70%. Manufacturing tolerances of discharge lamps result in variations of ±5% in the light flux of individual lamps. However, this will not seriously affect the average efficiency of a lighting installation.

Energy conversion

The energy conversion for lamps (Figures 7.2 and 7.7) shows a large difference between the energy input and useful energy output (in the form of PAR). For HPS lamps, the output is approximately 30% of the input (exclusive ballast). In addition, the efficiency of photosynthesis is relatively low. All these energy losses are ultimately released as heat, which, during the colder months, can be utilized for heating.

8a Luminaires (Fixtures) *Europe*

Introduction

A luminaire consists of a lamp bulb, reflector, and a housing with starter, ballast, capacitor and filter coil (optional). Apart from the reflector, the various components are connected with each other in an electrical circuit. Luminaires are usually designed to operate at one of several different input *voltages*. The internal components (ballast and capacitor) convert the input *voltage* so that the correct *voltage* is provided to the lamp. Various countries use different frequencies (AC power) and luminaires are designed to operate under these different systems.

8a.1 Electrical circuitry/wiring

8a.1.1 European system

An European luminaire is designed with the starter connected in series (Figure 8a.1).

8a.1.2 North American system

The schematic of a North American luminaire is shown in Figure 8a.2, see also in Section 8*b*.

8a.1.3 Differences between both systems

The European design has the advantage that ballast losses are smaller. The greatest drawback of this design is the relatively large impact of supply line *voltage* variations. Moreover, this design can only operate using line voltages between 200 and 250 volt.

Generally, the North American line voltage is higher between phase and zero. This makes it impossible to use the European design. If the *voltage* in North America is between 200 and 250 volt, it is usually a ‘phase-phase’ system. In that case, it is recommended for reasons of safety to choose the American system using a so-called ‘double isolation unit’. This means that the secondary coil is isolated for safety reasons, because it may happen that the luminaire, due to one phase dropping out, is still dangerously “hot” (charged).

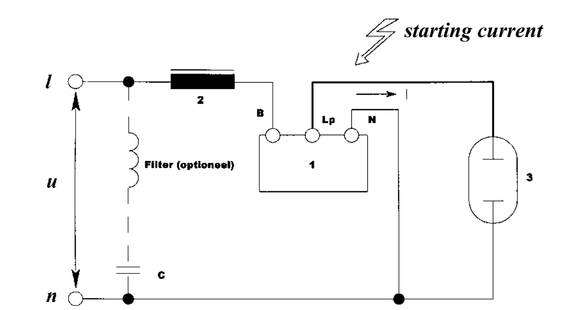
8a.2 Description of components

The components of the luminaire, which are housed in the (aluminum) enclosure, are discussed below.

8a.2.1 Ballast

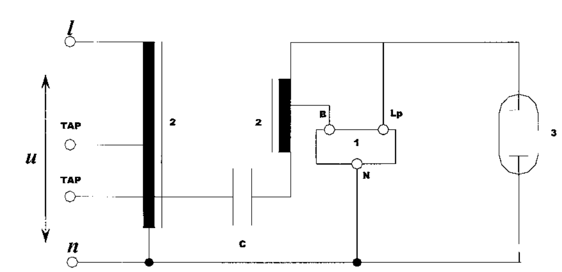
The filament in an incandescent lamp has a natural *ohmic* resistance, which inhibits unlimited passage of the current through the filament. In gas discharge lamps, the current passes through a metal vapor. The resistance of a metal vapor lamp is extremely low. Without special provisions the current may run so high that the lamp life becomes extremely short. To avoid this, the circuit contains a separate resistance which limits and stabilizes the current at the desired level. In principle, the current passing through a gas discharge lamp can be controlled with an ohmic resistance. This is done in some lower *wattage* lamps. A serious drawback, however, is that such a resistance loses much energy, in the form of heat. An alternative method is the use of an inductive resistance

Figure 8a.1. ***European luminaire design (starter connected in series).***



1 = starter, 2 = ballast, 3 = lamp, C = capacitor
B = ballast connection, Lp = lamp connection, N = neutral wire connection
n = neutral, u = line voltage, l = “hot” wire connection

Figure 8a.2. ***North American luminaire design.***



1 = starter, 2 = ballast, 3 = lamp, C = capacitor, TAP= connection point
B = ballast connection, Lp = lamp connection, N = neutral wire connection
n = neutral, u = line voltage, l = “hot” wire connection

or choke coil, also called ballast. In comparison with an *ohmic* resistance this greatly reduces the energy loss. Optimizing a ballast is very important for optimal operation of the lamp. The impedance and its tolerances should be as close as possible to the nominal value required for the lamp. In addition, the design and the materials used determine how large the internal losses of a ballast will be. The better the design and use of materials are, the larger the energy savings will be.

8a.2.2 Starter

High-Intensity Discharge (HID) lamps ignite only with a high voltage peak, because the discharge tube contains a gas mixture which has a very high resistance under cold conditions. As soon as the lamp ignites, the starter switches itself off automatically. The (European-type) starters shown in Figures 8a.3 and 8a.4, are connected in semi-parallel and in series, respectively. If a lamp bulb fails, or if there is no lamp in the fixture, the starter will keep trying to start the bulb. This situation may adversely affect the lifespan of the luminaire. Besides the loss of light, it is recommended for this reason not to wait too long before replacing a failed lamp bulb. There are starters available which switch themselves off after a certain amount of time. To date these type of starters are relatively expensive and therefore not frequently used in the greenhouse industry.

8a.2.3 Capacitor

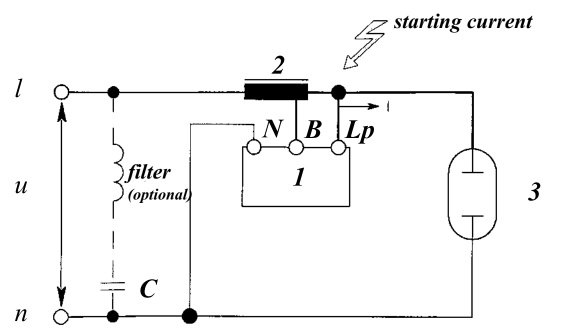
In addition to its very useful function of controlling the current moving through a lamp bulb, a ballast has also less favorable electrical characteristics. Its use results in a phase shift between the current through the lamp and the voltage across the lamp. This shift is expressed with the term cos ϕ, or cosine *phi* (also called the power factor) of the luminaire. This shift can be limited using a capacitor. Without a capacitor, cos ϕ will be around 0.45i (i = *induction*), but

Electric energy and power
*The relationship between current flow (**I**) in ampere (**A**) through a filament and the potential or voltage difference in volt (**V**) between the two sides (terminals) of a filament is given by* ***Ohm's Law**: $V = I \bullet R$,*
in which R is the resistance of the filament, expressed in ohm (Ω).
*The power **P** is the energy released per second, expressed in watt, in formula : $P = V \bullet I$*
The electrical energy can be released for example as radiation and heat.

Harmonic cycle
The diagram of a harmonic cycle is a sine curve or wave, such as L_1, L_2 and L_3 in Figure 8a.6. A complete cycle has a maximum above and a minimum below the x-axis. The number of cycles per second is the frequency and is expressed in hertz (Hz). In Figure 8a.6 (top graph) the cycles L_1, L_2 and L_3 have the same frequencies, but differ in phases. The phase is half of a complete cycle.

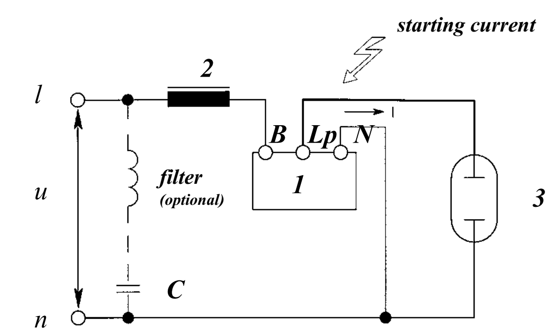
Power factor
The power factor is the cosine of the phase shift between current and voltage, expressed as cosϕ (with values between 0 and 1). If this factor has a value less than 1, less of the potential active power is used. This is a drawback since only active power determines the useful active energy, for example expressed in kWh.
The price per kWh active energy increases when the average power factor drops below a value of 0.8.
For HPS lamps, the power factor is less than 1.
Adding a capacitor increases the power factor. This increases the operating efficiency by using less power.

Figure 8a.3. **European-type starter (in semi-parallel).**



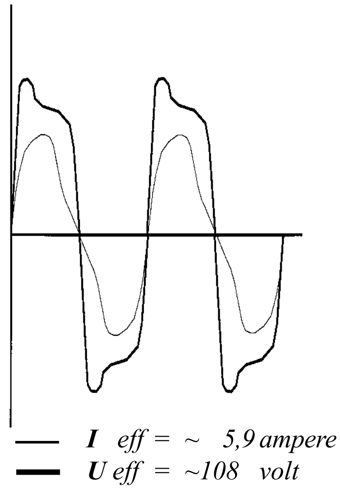
1	=	starter	B	=	ballast connection	n	=	neutral
2	=	ballast	Lp	=	lamp connection	u	=	line voltage
3	=	lamp	N	=	neutral wire connection	l	=	"hot" wire connection
C	=	capacitor						

Figure 8a.4. **European-type starter (in series).**



1	=	starter	B	=	ballast connection	n	=	neutral
2	=	ballast	Lp	=	lamp connection	u	=	line voltage
3	=	lamp	N	=	neutral wire connection	l	=	"hot" wire connection
C	=	capacitor						

Figure 8a.5. ***Lamp current and voltage for a 600 watt HPS lamp.***



with a capacitor cos ϕ will be >0.85i. This value complies with the minimum value of 0.85i required by most electric utilities.

8a.2.4 Filter coil

The local electric utilities use high-frequency line signals to switch electrical installations on or off, such as streetlights, boilers, and kWh meters. Large supplemental lighting installations can have a negative influence on these line signals due to the use of capacitors. To avoid this, the local utility company may require the use of filter chokes before the installation of a supplemental lighting system can be approved.

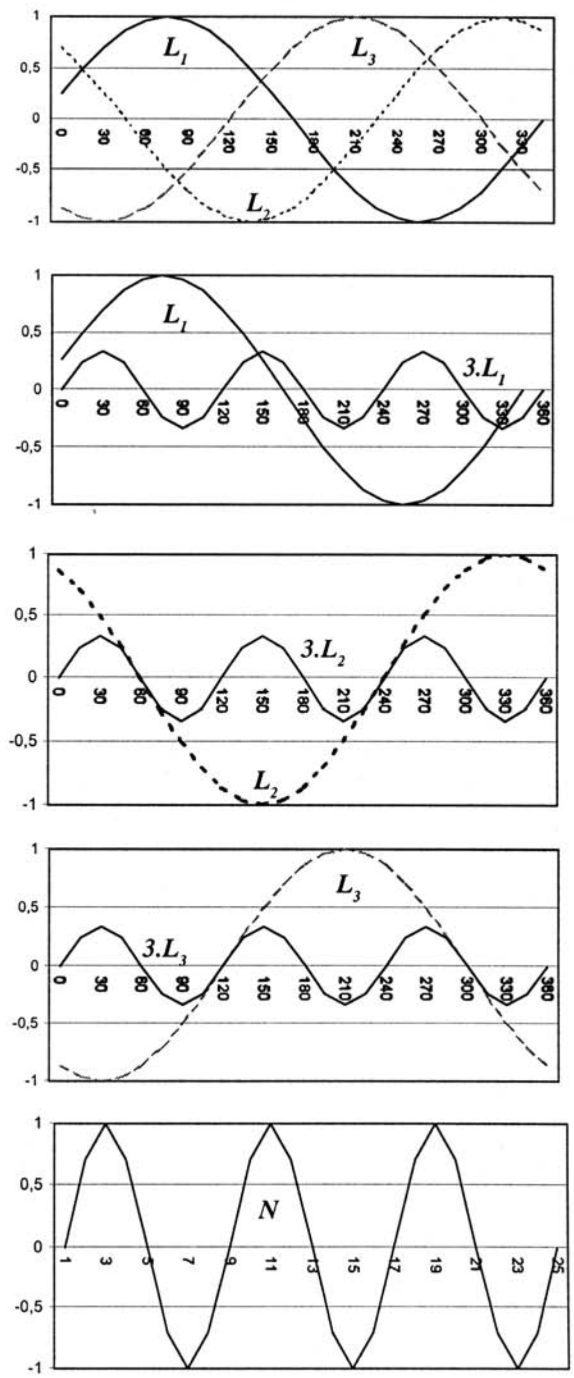
8a.3 Harmonic currents

Gas discharge lamps do not have a linear characteristic. As a result, the sine-shaped *line voltage* leads to harmonic currents (zero-current in the electric circuit). A gas discharge lamp has the tendency to go out every time the *voltage* passes through zero. Therefore, the current through the lamp does not have a pure sine form, but rather a block waveform (Figure 8a.5). As a result of this deformation, the lamp returns a current through zero, referred to as zero-current. This zero-current consists of frequencies higher than the base frequency. The share of the 3rd (3 x 50 Hz = 150 Hz), 5th and 7th harmonic current is of substantial importance. This current is at most one third of the phase current, consequently in a 3-phase system the current through zero can be no more than (3 x 1/3) the phase current.

Resonance

The current through zero has a basic frequency of 150 Hz, because the 3rd harmonic current is the most strongly represented. If in a lighting installation fixtures are connected only to a generator or transformer, it might happen that, as a result of unilateral load and the electrical characteristics of the installation, a resonance (winding up of energy) develops between the installation and the fixtures. Measurements can reveal this when the zero-current becomes higher than the phase currents. The immediate consequence is often overheating of the control panels. Furthermore, it leads to higher power inputs and increased electricity costs. If this happens, immediate action has to be taken. A possible solution might be to install a filter choke in the smallest controllable unit.

Figure 8a.6. ***Harmonic electric currents.***



The third harmonic current is added into the zero-current.

8b Luminaires (Fixtures) *North America*

Introduction

A luminaire consists of a lamp bulb, a mogul socket, a reflector, and an enclosed housing containing a ballast kit including a transformer, ignitor, and a capacitor. Aside from the reflector, the various components are connected to each other in an electrical circuit. Luminaires are designed to operate at one of several different voltages. Different installations use different frequencies (AC power) and luminaires are designed to operate under these different systems.

8b.1 Electrical circuitry/wiring

8b.1.1 European system

The schematic of a European luminaire is shown in Figure 8b.1 (See also Section 8a).

8b.1.2 North American system

The schematic of a North American Constant Wattage Autotransformer is shown in Figure 8b.2.
The schematic of a North American Constant Wattage Isolated transformer is shown in Figure 8b.3.

8b.1.3 Differences between the two systems

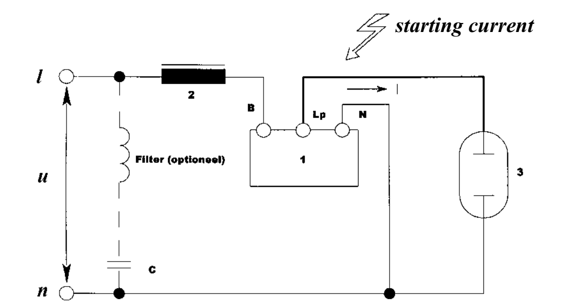
The European design has the advantage that there is less ballast loss, meaning the input wattage needed to power the luminaires is less than that of the North American luminaires. However, there are limitations to using the European luminaires in North America. The first limitation is that European luminaires are designed to operate using line voltages ranging between 200 and 250 VAC. Thereby, it eliminates the possibility of using the 347VAC or 480VAC power supplies available in North America. The inability to use these higher voltage luminaires significantly increases the initial capital investment for installation.

The higher voltage luminaires draw less amperage per unit compared to its European counterpart, therefore they require fewer breakers to be installed.

The second drawback to using a European system in North America is that many North American systems use a "phase to phase" system. North American ballasts are manufactured in such a way that the secondary coil, which contains the power supply leads, is isolated from the rest of circuitry for safety reasons. Therefore, if one of the phases were to drop out, the unit would not be dangerously charged, where as, if a European fixture was operating on a phase to phase system and a phase were to drop out, the luminaire could still be dangerously charged.

A third, and most critical drawback, is the fact that the "simple reactance type ballast" used in the European luminaire does not conform to Canadian Standards Association and Underwriters Laboratory approvals for high-intensity discharge (HID) luminaires.

Figure 8b.1. ***European luminaire design (starter connected in series).***



1	=	*starter*	*B*	=	*ballast connection*	*n*	=	*neutral*
2	=	*ballast*	*Lp*	=	*lamp connection*	*u*	=	*line voltage*
3	=	*lamp*	*N*	=	*neutral wire connection*	*l*	=	*"hot" wire connection*
C	=	*capacitor*						

8b.2 Description of components

The ballast components, which are housed in the extruded aluminum enclosure, are briefly described below.

8b.2.1 Ballast

High-Intensity Discharge lamps require a core and coil, known commonly as a ballast. A ballast limits and stabilizes the current passing through a gas discharge lamp and greatly reduces the loss of energy in the form of heat.

The two conventional ballasts used in North America are the Constant Wattage Autotransformer (CWA) and the Constant Wattage Isolated (CWI) transformer.

The two ballasts are relatively designed to function the same way. Both units incorporate a capacitor in series with the lamp and regulate a wide range of input voltages and hold the lamp wattage to a narrow range. This avoids the overdriving of the bulb, resulting in longer bulb life. The only major difference between the two is shown in the names of the ballasts. The CWI ballast isolates the secondary windings, which contains the voltage supply leads, from the rest of the electrical circuit.

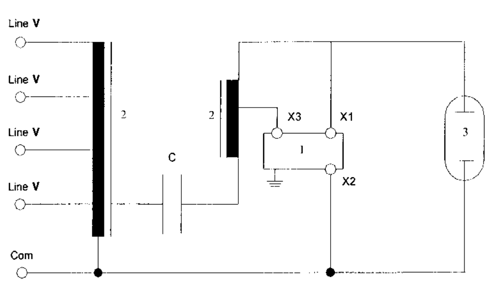
8b.2.2 Ignitor

High-Intensity Discharge lamps will only ignite after receiving a high voltage peak. The gases contained in the discharge tube have a very high resistance under cold conditions. The ignitor is responsible for pulsing that high voltage peak to the lamp. Once the lamp has ignited, the ignitor will switch itself off automatically. In the event that there is a lamp that will not ignite, or the lamp has been removed from the luminaire, the ignitor will still send its high voltage pulse to through the circuit. By doing this, the lifespan of the luminaire is adversely affected. Besides the loss of light, this is the reason it is recommended to replace the failed lamp as soon as it is noticed not to be working. There are ignitors available that stop pulsing after a certain time if there is a defective lamp in the luminaire. However, they are relatively expensive compared to the conventional ignitors and therefore not frequently used in the greenhouse industry.

8b.2.3 Capacitor

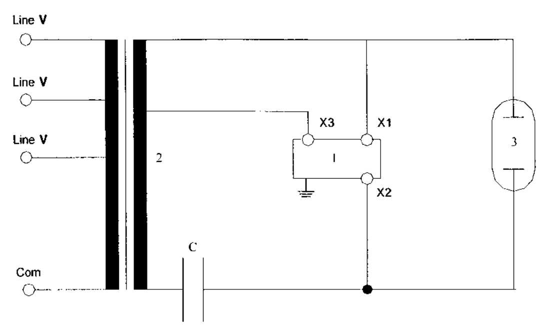
Capacitors serve two major purposes in a HID luminaire. The first and most widely known, the capacitor effectively limits the current moving through the lamp bulb. Secondly, it stabilizes the less favourable electrical characteristics of the ballast. Incorporating a capacitor in the ballast of a luminaire results in a phase shift between the current of the lamp and the voltage across the lamp. This is commonly known as the ballast's power factor. The formula used to determine the ballast's approximate power factor is the quotient of the ballast manufacturers' lamp type specification divided by the input power. For example, for a 600 w-fixture, the manufacturer's lamp type is 600 w. The input wattage is 675 watt. Therefore, according to the formula, 600 w divded by 675 w equals 0.88. In order for a luminaire to operate at it's peak potential, the ballast's power factor should range between 0.8 and 0.9. Without the capacitor, the ballast's power factor would only be approximately 0.45.

Figure 8b.2. ***North American Constant Wattage Autotransformer (CWA) wiring diagram.***



1 = ignitor X_1 = lamp connection C = Capacitor
2 = ballast X_2 = common connection Com = Common, or neutral wire
3 = lamp X_3 = ballast connection
Line V = voltage tap

Figure 8b.3. ***North American Constant Wattage Isolated (CWI) transformer wiring diagram.***



1 = ignitor X_1 = lamp connection C = Capacitor
2 = ballast X_2 = capacitor connection Com = Common, or neutral wire
3 = lamp X_3 = ballast connection
Line V = voltage tap

9a Luminaires by Hortilux Schréder B.V.

Description of the HS2000 (HPS) luminaire

9a.1 Construction of the HS2000 luminaire

The luminaire consists of:

1. Complete aluminum housing, including an upper and a lower compartment (removable), in which ballast, starter and capacitor are mounted. The reflector is connected at the front with a standard adapter secured with a bolt and wing nut.
2. The reflector is made of high-quality, polished and anodized (*i.e.* electrolytically oxidized) aluminum including a universal adapter.
3. A mounting profile (top plate) of extruded (*i.e.* pressed in a certain shape) aluminum, mounted on top of the fixture, and including a cut-away for mounting bolts, with which various suspension brackets can be fastened. For most common mounting systems, Hortilux Schréder has standard brackets available.

9a.2 Technical description of the HS2000 luminaire

The unit consists of a slender aluminum upper and lower compartment. The lower compartment is provided with two bolts to close the unit. In compliance with international testing regulations, the used material is heat and UV resistant, impact-resistant, nonflammable and waterproof for drip (IP23). Due to the use of aluminum, the unit must be grounded.
The use of extrusions, cut-a-ways in the lower compartment, and ventilation holes below the top plate, result in a so-called Venturi effect in the unit (Figures 9a.1 and 9a.2). This Venturi effect accelerates the ventilation rate. To obtain additional cooling, the unit is divided by an aluminum partition into two compartments. Located in the front part of the unit are the lamp base and the ballast (a component that emits heat). In the back part, the starter and the capacitor are mounted. Thanks to the Venturi effect and the partitioning, a very low operating temperature is achieved in the part of the unit with the critical components. This is beneficial to the lifespan of the temperature-sensitive parts (capacitor and starter).
To install the fixture, two bolts need to be loosened in the lower compartment. Next, the complete lower compartment can be moved aside using a hinge. This opening design makes it very easy to install the fixture quickly. In case of service, the lower compartment can be removed and repaired on the spot. If replacement is required, the lower compartment containing all major components can be removed after disconnecting the power, and a spare lower compartment can be easily installed. In this way, it is not necessary to disassemble or replace the complete luminaire. In addition, the electric wiring need not be disconnected.

Figure 9a.1. Venturi effect inside the housing of the HS2000 luminaire.

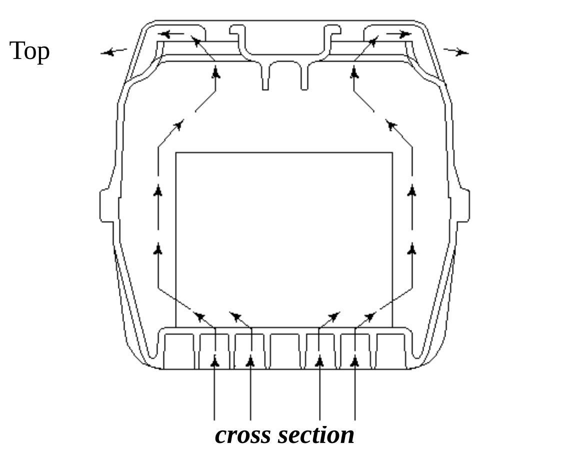


Figure 9a.2. The HS2000 (Midi) luminaire. This luminaire is designed to minimize the shade effect.

Table 9a.1. ***Characteristics of the HS2000 400/600 watt (HPS) luminaire.***

	HS2000 400 watt	**HS2000 600 watt**
Current (at 230 V)	2.3 A	3.3 A
Voltage	220-240 V	220-240 V
Frequency	50 Hz	50 Hz
Luminaire wattage	445 watt	645 watt
Tolerance lamp / ballast	± 5%	± 5%
Power factor (cos ϕ)	>0.85i	>0.85i
Weight (including reflector and lamp)	± 9 kg	± 11 kg

9a.3 Characteristics of the HS2000 400/600 watt luminaire

Table 9a.1 shows the most important electrical data for the HS2000 luminaire. Additional characteristics are described below. Table 9a.2 provides information about the light intensity and the number of luminaires installed per square meter for different luminaire configurations.

- Isolation class 1, ENEC, KEMA, IP23, CE-marking;
- Compact aluminum housing, resulting in a minimal shade effect;
- Two separate compartments (ballast, lamp base, and other components);
- Low operating temperature of capacitor and starter;
- Standard option for including a filter coil;
- Reflectors with a very high reflection efficiency;
- Five different reflectors attachable through a universal adapter;
- Reflectors can be changed easily and quickly;
- Large connection compartment with ample space for a maximum of five 2.5 mm² cables;
- Easy screw-type connectors;
- The fixture can be connected and mounted quickly
- Different lamp types, voltages and or frequencies available upon request.

9a.4 Reflector

The most important part of the HS luminaire is the reflector. This 'high-tech' reflector is the key component for the success of these HS luminaires made by Hortilux Schréder B.V.

9a.4.1 General

Most luminaires for plant lighting are stand-alone light sources. To provide as much light to the plants as possible, the luminaires are equipped with a reflector. In its research laboratory, Hortilux Schréder has developed reflectors of very high-quality aluminum. These reflectors receive and reflect the light into the desired direction. As a result, the light is evenly distributed over the crop. The uniformity of the light depends on the type of reflector, the distance between lamp and crop, and the distance between the fixtures (mounting pattern).

Hortilux Schréder B.V. supplies as many as five different reflectors, each with a very high light reflection efficiency. This technique allows the perfect light distribution for every situation.

All reflectors are made out of one piece of aluminum and are guaranteed to be uniform.

The reflectors are made of pure aluminum, which is subsequently polished and anodized. The microscopically small facets at the surface are responsible for a diffuse light pattern and reduce the accumulation of dirt.

The reflectors can be removed quickly and easily for cleaning.

Besides the correct curvature and shape of the reflector, the various surface treatments are of essential importance. Customers can choose between a mat-finished and a high-gloss reflector.

9a.4.2 Surface treatment of reflectors

After extrusion in special moulds, the reflectors are degreased and stripped of all contaminations from the various treatments in the factory. Next, the following three steps lead to the final end product.

1. Polishing

In this process the microscopically small 'hills' and 'valleys' at the surface of the reflector are chemically cleaned. This is necessary to obtain, after the anodizing treatment, a high degree of reflection from the reflector surface.

2. Anodizing treatment

In this process, the reflector is immersed in a bath of sulfuric acid (H_2SO_4) of a certain temperature. Next, a very high current (2,100 A) passes through the bath and the reflectors, which are clamped in titanium contacts. As a result, the surface undergoes a chemical change. A layer of aluminum oxide (Al_2O_3) develops. This aluminum oxide coating is extremely hard and protects the reflector against chemical influences. In addition, this layer is responsible for the correct surface structure, making the reflected light diffuse and very uniform.

3. Sealing

During sealing, the microscopically small holes which developed during the anodizing treatment, are filled. The aluminum oxide layer binds in this special sealing bath with water into bohemide, a naturally occurring mineral. In addition, this sealing process provides further protection against external influences.
Mat-finished reflectors have a different optical effect than high-gloss ones. Mat-finished reflectors reflect diffusely, high-gloss reflectors reflect selectively. Due to minor imperfections in the curvature of the surface of the high-gloss reflector, the light distribution sometimes exhibits a frayed pattern. Uniformity plays a crucial role in supplemental lighting, and for this reason mat-finished reflectors are generally preferred.

9a.4.3 Type of reflector and efficiency

The efficiency of a reflector can be assessed based on a polar diagram (*e.g.* Figures 9a.3 and 9a.4). Such diagrams show how reflectors distribute light in different directions. Depending on the light distribution, a distinction can be made between deep-radiating, wide-radiating and superwide-radiating reflectors. To determine the difference between the various reflector types, the reflection angle is measured below which the reflector emits 80% of the light. The classification is as follows:

	Reflection angle	Reflector
Deep-radiating	0 - 60º	**Deep**
Wide-radiating	0 - 70º	**Wide**
Superwide-radiating	0 - >75º	**SuperWide**

The **HS2000 Midi reflector** is intermediate between the deep-radiating and wide-radiating reflector, because it emits 80% of the total light quantity between a reflection angle of 0 and 65º.
The reflector efficiency is defined as the ratio between the light flux produced by the lamp bulb and the light flux radiated by the reflector. The losses occurring in the reflector are mainly the result of absorption of light by the surface of the reflector. In addition, the

Figure 9a.3. ***HS2000 Deep reflector, polar diagram, luminaire dimensions (cm).***

Figure 9a.4. ***HS2000 Midi reflector, polar diagram, luminaire dimensions (cm).***

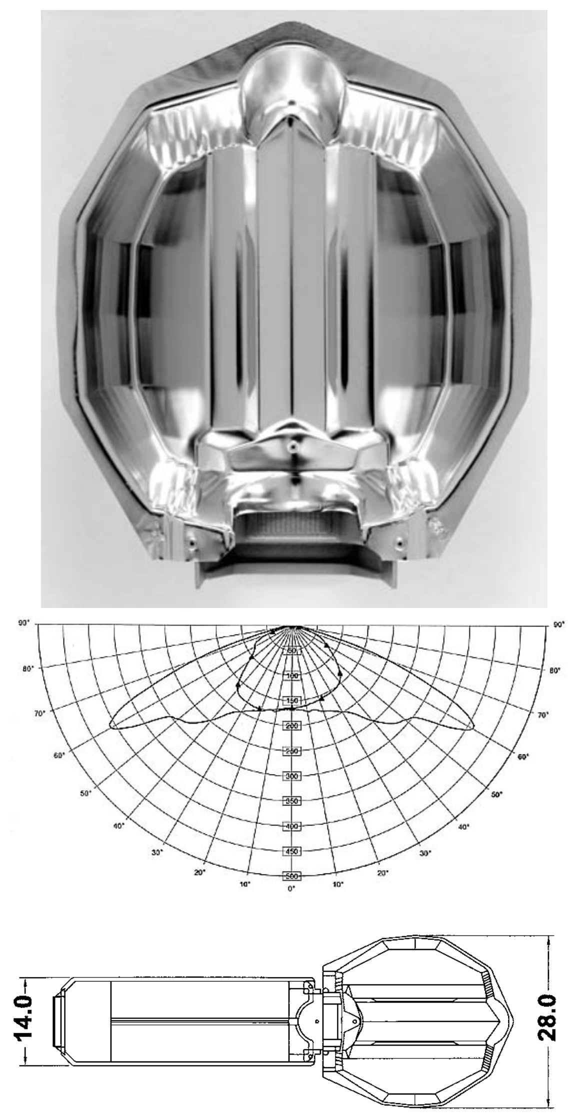


Figure 9a.5. ***HS2000 Medium reflector, polar diagram, luminaire dimensions** (cm).*

shape, the dimensions, and the various surface treatments of the reflector material also affect the reflector efficiency. Currently, Hortilux Schréder B.V. reflectors have an efficiency of 90%, which is high in comparison with reflectors used for ‘ordinary’ lighting purposes.
Which type of reflector is suitable for a given greenhouse application is determined by Hortilux Schréder B.V. on the basis of a number of criteria, including for instance the available distance between the luminaire and the top of the crop canopy.

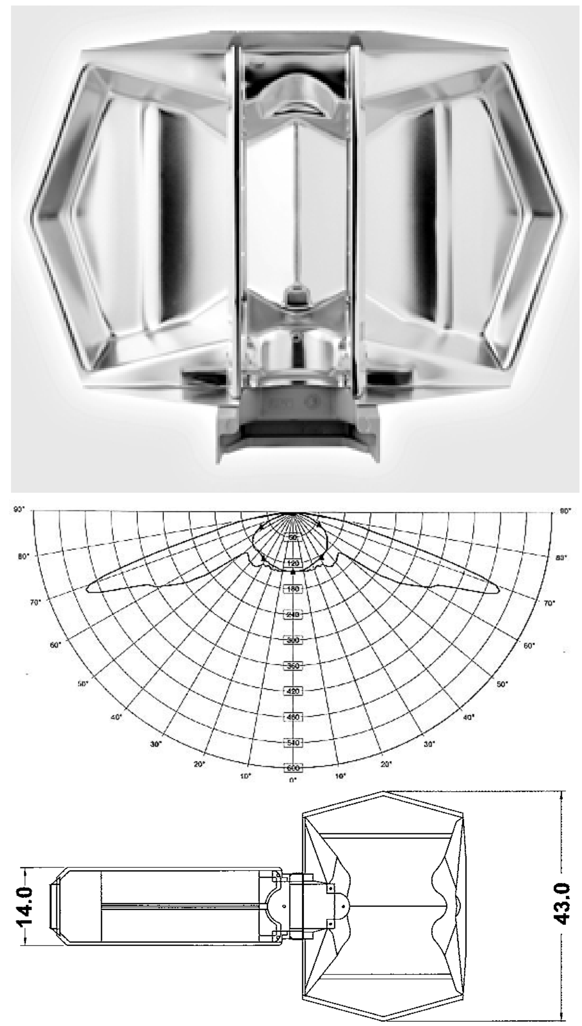
9a.4.4 Deep reflector (Figure 9a.3)

This deep-radiating reflector is:
- Especially designed for a square mounting pattern;
- Deep irradiation into a crop;
- Suitable for 400/600 watt lamps.

9a.4.5 Midi reflector (Figure 9a.4)

This deep-radiating reflector is:
- Especially designed for 8.0 and 9.6 m (26 and 32 ft, resp.) wide greenhouse bays;
- Also suitable for 6.40 m (21 ft) wide greenhouse bays;
- Suitable for 400/600 watt lamps.

Figure 9a.6. ***HS2000 Wide reflector, polar diagram, luminaire dimensions** (cm).*



9a.4.6 Medium reflector (Figure 9a.5)

This deep-radiating reflector is:
- Designed for more rectangular mounting patterns;
- Suitable for deep irradiation into the crop;
- Suitable for 400/600 watt lamps.

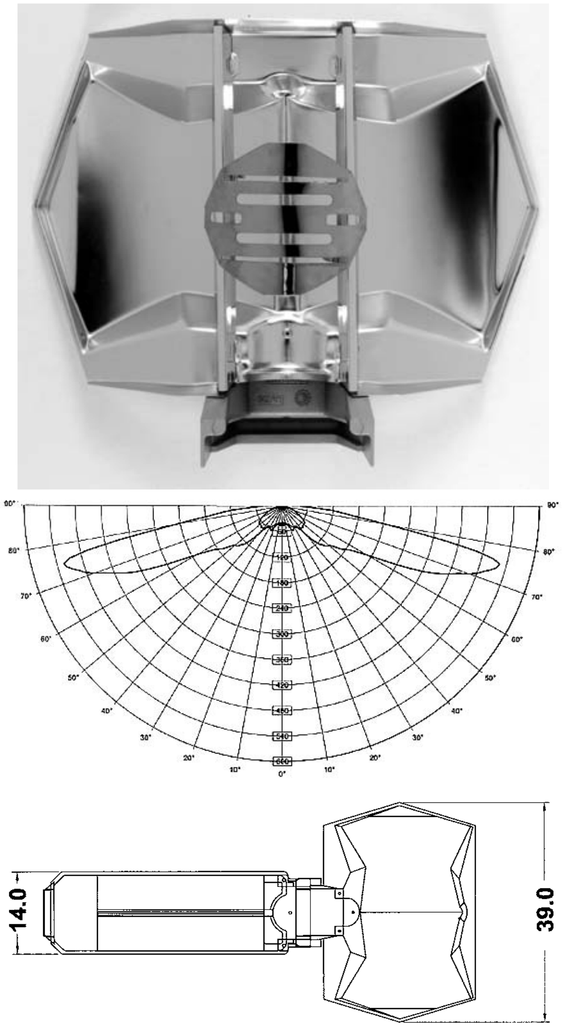
9a.4.7 Wide reflector (Figure 9a.6)

This wide-radiating reflector is:
- Designed for more rectangular mounting patterns;
- Equipped with two different screens (secondary reflector) for optimum light distribution;
- Suitable for 400/600 watt lamps.

9a.4.8 SuperWide reflector (Figure 9a.7)

This superwide-radiating reflector is:
- Designed for more rectangular mounting patterns;
- Equipped with a screen for optimum light distribution;
- Suitable for 400 watt lamps.

Figure 9a.7. ***HS2000 SuperWide reflector, polar diagram, luminaire dimensions (cm).***



9a.5 Cleaning

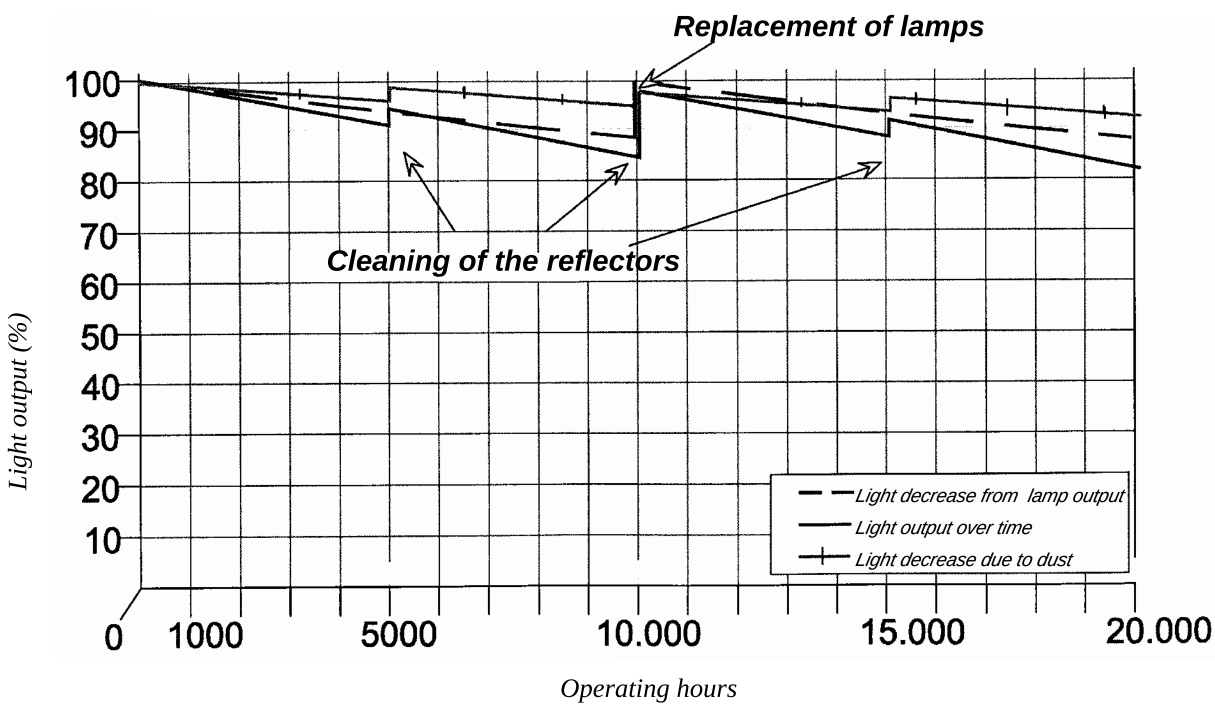
To get the highest output from supplemental lighting systems for a prolonged period of time, maintenance is very important. Research demonstrated that the degree of dust accumulation on the reflectors highly depends on factors like the greenhouse construction, type of crop, particular circumstances, and operating hours. Firm data is hard come by. Sometimes the performance declines with 15% over a period of 3 to 4 years, other times only 8% in 9 years (Figure 9a.8). Regular cleaning of the reflectors and lamps is highly recommended (as a rule of thumb, 1% more light results in 1% more growth). It is a good idea to consider all the external influences leading to dust accumulation, including the question how it can be prevented. Maintenance of the electrical equipment is discussed in Section 11.4.

Dust accumulation
Activities resulting in dust accumulation can be roughly divided into four main groups.

1. Soil tillage
Soil tillage creates a lot of dust and this precipitates as a deposit on the inside of the reflector and on top of the lamp inside the reflector.

2. Motorized equipment used in the greenhouse
Motorized equipment used in the greenhouse frequently operates with the help of a combustion engine. The exhaust gases contain fatty smuts, which attach themselves to the reflector surface. Using the greenhouse ventilation system to reduce these deposits helps but usually does not completely prevents it.

Figure 9a.8. ***Estimated decrease in light output due to aging of the lamp and dust accumulation over time.***



3. Irrigation

Water drops from overhead irrigation systems may precipitate on the reflector surface. After drying they leave white lime scale, which can only be removed with aggressive cleaners.

4. Crop protection and other treatments

Contamination may come from crop protection agents (both from high volume and low volume applications) but also from large-scale welding activities, which release sulfurous vapors. The combination with moisture leads to sulfuric acid, which has a corrosive effect on metals such as the ones used in reflectors.
Dust accumulation cannot always be avoided. But regular cleaning does not give the surface contamination the opportunity to permanently attach itself to the reflector and lamp. Cleaning is most effective when conducted just before the start of the new lighting season.

Cleaners

Minor dust accumulation

Cleaning the reflector with a soft cloth and an alcohol-based cleaner is recommended. If pre-rinsing is required, de-ionized (or de-mineralized) water should be used. This does not contain salts and prevents the reflector from becoming dull.
Lime scale on the reflector surface can only be removed with a mild acid such as household vinegar. This should, however, be used cautiously because these (acid) compounds can affect the aluminum reflector surface.

Persistent dust accumulation

When regular cleaning is skipped the dust accumulation frequently become more difficult to remove. If this is the case, a special metal cleaning agent should be used. Such compounds, which have an etching effect, take away a very thin layer of the anodized coating during cleaning. When such compounds fail to work, two final options remain: re-anodizing or a new reflector.

Re-anodizing

Dust accumulation reduces the light output from the luminaire, while using the same amount of electric energy to operate the lamp. The result is reduced plant growth while the electricity costs remain the same.
Research showed that the loss in income can be significant. If cleaning gives unsatisfactory results, re-anodizing may be an option. Re-anodizing means that the dirty reflector undergoes the chemical end-treatment, *i.e.*, the anodizing process (Section 9a.4.2), preceded by a very thorough cleaning. This results in a virtually new reflector, with the corresponding high efficiency.
When dust accumulation becomes severe (*e.g.* a 10% reduction in reflector efficiency) re-anodizing usually becomes profitable, depending on the type of reflector. The costs for re-anodizing reflectors are approximately 30% of the costs for purchasing entirely new reflectors. It is recommended to consult lighting specialists for these problems. They can provide you with extensive information on reflector measurements and suggest possible solutions for optimizing the reflector efficiency and the accompanying costs.

Table 9a.2. ***The relationship between HPS luminaire density (square meters per luminaire) and light intensity.*** *The data are derived from installations with at least 8 x 8 luminaires (fixtures) and a nominal light output from the lamps of 55,000 (400 W) and 87,000 (600 W) lumen, respectively. The data in the table is for illustrative purposes only and is not a guarantee for specific installations.*

Light intensity		MIDI 400 watt	MIDI 600 watt	DEEP 400 watt	DEEP 600 watt	WIDE 400 watt	WIDE 600 watt
lux	*µmol* m^{-2} s^{-1}	*m^2 of floor area for each luminaire*					
2,500	**29**	18.5	-	19.0	-	18.2	-
3,000	**35**	15.5	24.6	15.9	25.2	15.2	23.8
3,500	**41**	13.3	21.1	13.6	21.6	13.0	20.4
4,000	**47**	11.6	18.5	11.9	18.9	11.4	17.9
4,500	**53**	10.3	16.4	10.6	16.8	10.1	-
5,000	**59**	9.3	14.8	9.5	15.1	9.1	-
6,000	**71**	-	12.3	-	12.6	-	-
7,000	**83**	-	10.6	-	10.8	-	-

9b Luminaires by P.L. Light Systems, Inc.

Description of the PL2000 luminaire

9b.1 Construction of the PL2000 luminaire

Each luminaire manufactured by *P.L. Light Systems, Inc.* consists of:

1. A complete extruded aluminum enclosure houses the ballast, ignitor and capacitor. The interlocking aluminum pieces are secured together by two punched aluminum plates. The endplate has an opening for the power supply cable to be inserted and secured. The frontplate has the lamp mogul socket attached to it along with the specially designed reflector-mounting collar.

2. One of six styles of reflectors, made of high quality, polished and anodized aluminum, is secured to the mentioned reflector mounting collar using its own unique adapter and locked into place by a bolt and wing nut.

3. The top piece of extrusion is designed to easily fit an adequately sized bolt to mount the unit. *P.L. Light Systems, Inc.* can provide various mounting brackets.

9b.2 Technical description of the PL2000 luminaire

The unit is a slender, streamlined aluminum extrusion. Four pieces of interlocking aluminum are joined together and held secure by two aluminum plates. Screws are provided to secure the endplate to the luminaire once the electrical hook up is completed. The fixture contains the ballast kit, with the ballast positioned behind the frontplate and the ignitor and capacitor strapped to a mounting plate. The mounting plate also acts as a divider to fend off some of the heat produced by the ballast. To further aid in the cooling of the components, each of the side plate extrusions have fifteen louvre openings punched into them, (Figures 9b1 and 2). The heat sinks incorporated into the top and bottom extrusions also aid in the dissipation of heat throughout the luminaire. As a result the heat sensitive components run well below their heat tolerances, resulting in longer life expectancies.

Canadian Standards Association and the Underwriters Laboratory are the governing bodies that regulates product safety and certification in North America. *P.L. Light Systems, Inc.* has made it their policy to ensure that all of our luminaires meet these requirements. In accordance with CSA specifications for Canada, any installation of luminaires, which are powered either by 208 or 240 VAC must have the lamp mogul, grounded.

The luminaires are non-corrosive, heat resistant, and water-resistant. Due to the use of aluminum, each unit must be sufficiently grounded.

With their user-friendly design, installation of the luminaires is relatively quick and simple. Depending on the method of electrical installation, most of the wiring can be done on ground level. Each luminaire is supplied with an endplate separate from the rest of the body. This endplate has a pre-punched opening to accept a suitable cable strain relief. The power supply feed wire is secured into the strain relief and then the connection is made to the power supply of the ballast. Once completed, the endplate is then secured to the luminaire with the screws provided.

Figure 9b.1. ***Heat dissipation pattern of a PL2000 luminaire.***

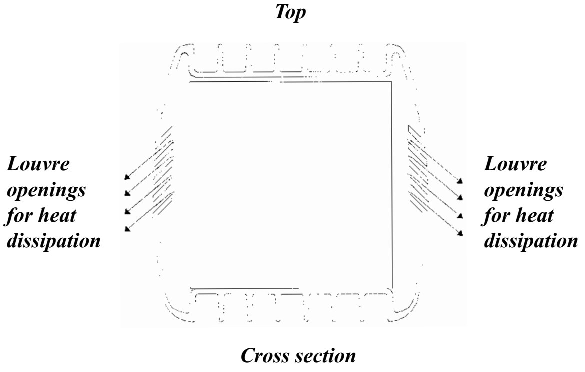
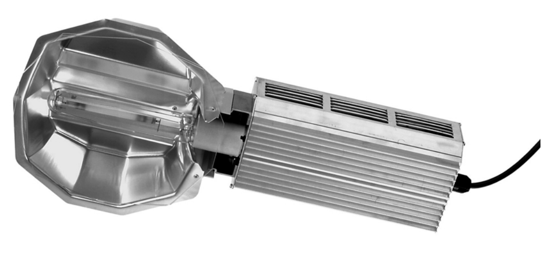


Figure 9b.2. ***PL2000 Medium luminaire.*** *This luminaire is designed to minimize the shade effect.*

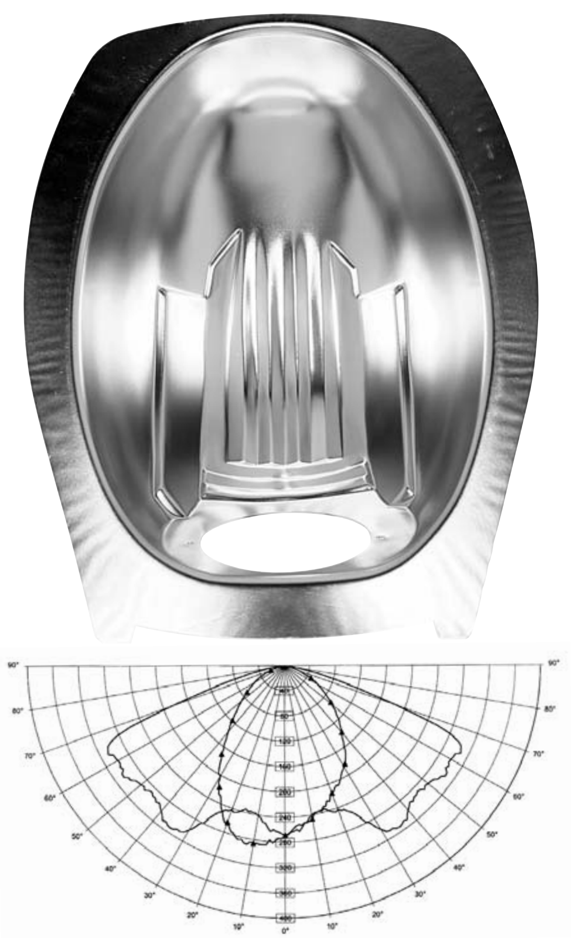


Tabel 9b.1. ***Characteristics of the PL2000 luminaire.***

Lamp Wattage	Voltage	Amperage Draw	Input wattage
PL2000 HPS			
150 watt	120/208/240/277/347/480	1.7/1.1/0.8/0.7/0.5/0.4	190
250 watt	120/208/240/277/347/480	2.5/1.5/1.3/1.1/0.9/0.7	295
400 watt	120/208/240/277/347/480	3.8/2.2/1.9/1.7/1.3/1.0	465
430 watt	120/208/240/277/347/480	5.2/3.0/2.6/2.3/1.8/1.3	490
600 watt	120/208/240/277/347/480	5.7/3.3/2.9/2.5/2.0/1.4	675
1,000 watt	120/208/240/277/347/480	9.5/5.5/4.8/4.2/3.3/2.3	1,100
PL2000 Metal Halide			
400 watt	120/208/240/277/347/480	4.0/2.3/2.0/1.7/1.4/1.0	460
1,000 watt	120/208/240/277/347/480	9.0/5.2/4.5/3.9/3.2/2.2	1,080

In case servicing is needed, the endplate is unscrewed from the unit, once the power supply has been shut off, and the components become easily accessible from the back of the luminaire. If replacement of the entire ballast kit is needed, the entire bottom extrusion can be slid out of the unit. The new ballast kit will have the bottom extrusion pre-fastened and pre-wired. The ballast is then slid into the rest of the unit and the only wiring required is first to the lamp mogul, and second to the power supply. The endplate is then screwed back on to the unit and the power supply is then turned back on.

Figure 9b.3. ***PL2000 with 1,000 watt reflector and polar diagram.***



9b.3 Characteristics of the PL2000 luminaire

Table 9b.1 shows the most important electrical data for the PL2000 luminaire.
Other features of the luminaire are listed below.

- CSA/UL certified;
- Slim aluminum housing, resulting in minimal shade effect;
- Two separate compartments (ballast and component);
- Low operating temperature;
- Reflectors with a high reflective efficiency;
- Six different reflectors available;
- Reflectors can be removed and replaced quickly;
- Sufficient room for connecting power supply wires;
- Fixture can be prepared and mounted quickly;
- Various lamp wattages and voltages available.

Commercial fixtures are also available in remote style configuration upon request.

10 Designing Supplemental Lighting Systems for Greenhouses

Sales and service

Hortilux Schréder B.V. and P.L. Light Systems, Inc. design supplemental lighting installations focussed on the needs of individual customers. For each single project, *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* calculate the most economic design, in other words: how to achieve the highest light intensity and uniformity using the fewest possible number of luminaires. *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* have an extensive global network through dealers and/or certified electricians for the delivery of services and products. For technical service, the grower, electrician, or consultant can contact *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* directly (Figure 10.1).

10.1 Requesting a lighting design quote

Lighting design

To be able to design an optimal lighting system, specific details about the greenhouse design and crop(s) are needed. For this reason, *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* request growers to complete a so-called lighting design quote form (Figure 10.2). The form solicits information about the grower, contractor, greenhouse design, requested light intensity, and height of the specific crop. In addition, a grower can indicate on the form the location of heating pipes, irrigation lines and/or other potential obstacles.

10.2 Designing supplemental lighting installations

In the design of a supplemental lighting installation the requests by the customer are combined with the calculations by *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* based on specific luminaire specifications. During this process, the full knowledge and extensive expertise of *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* are used. The result is an economic light-

Figure 10.1. Sales and services of Hortilux Schréder B.V. and P.L. Light Systems, Inc.

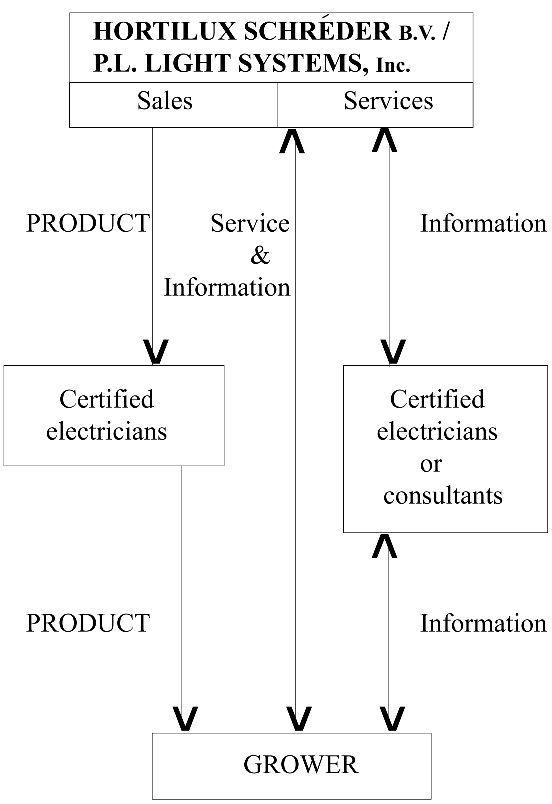
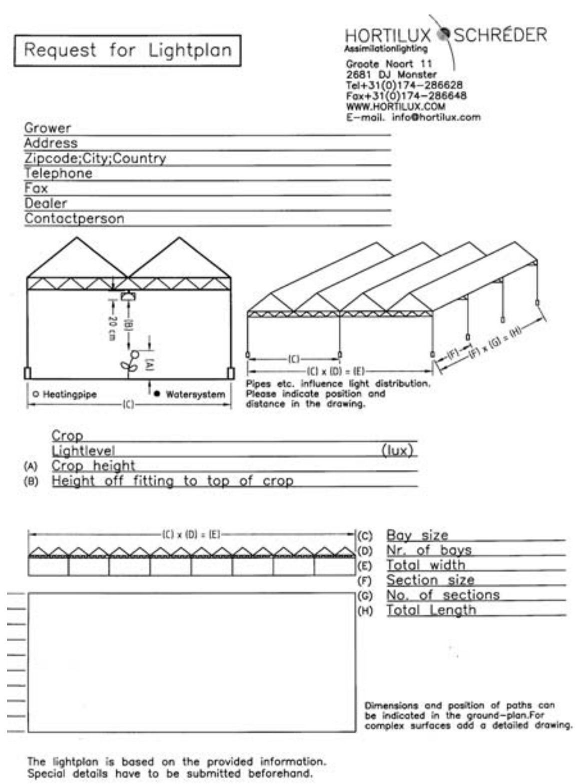


Figure 10.2. Requesting a lighting design quote.


Request for Lightplan

HORTILUX SCHRÉDER
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WWW.HORTILUX.COM
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Grower
Address
Zipcode;City;Country
Telephone
Fax
Dealer
Contactperson

-20 cm (B) (A)
Heatingpipe Watersystem (C)
(C) (C) x (D) = (E) (F) (F) x (G) = (H)
Pipes etc. influence light distribution. Please indicate position and distance in the drawing.

Crop
Lightlevel (lux)
(A) Crop height
(B) Height off fitting to top of crop

(C) x (D) = (E)
(C) Bay size
(D) Nr. of bays
(E) Total width
(F) Section size
(G) No. of sections
(H) Total Length

Dimensions and position of paths can be indicated in the ground–plan.For complex surfaces add a detailed drawing.

The lightplan is based on the provided information. Special details have to be submitted beforehand.

ing design including the number and location (mounting pattern) of the luminaires. The mounting pattern includes the pattern (*e.g.* square, rectangular, or staggered), the distances between the luminaires, and the distance between the bottom of the reflectors and the top of the crop canopy.

There are four parameters that determine the lighting intensity and the uniformity (Figure 10.3):

1. Type of luminaire and its reflector;
2. Distance (**H**) between the bottom of the reflector; and the top of the crop canopy (mounting height);
3. Distance (**L**) between luminaires measured within a row of luminaires;
4. Distance (**B**) between luminaires measured between rows of luminaires.

10.2.1 Uniformity

The mounting height determines, in part, the uniformity of the light distribution for a particular design. In addition to the mounting pattern, the reflector design determines the light uniformity. The distance between luminaire and crop is less critical for determinating the light intensity because luminaire light patterns start to overlap with increased mounting heights. Therefore, the light intensity does not change much when the mounting height is changed, as will be shown in the next section (see also Figure 10.4).

10.2.2 Computer calculations

Hortilux Schréder B.V. and P.L. Light Systems. provide computer generated light intensity and uniformity calculations (Figure 10.5) based on the information provided in the lighting design quote form (Figure 10.2) at a predetermined height. The calculations performed by the computer software are based on the polar di-

***Figure 10.3.* Luminaire mounting pattern.**
(The distances L, B, and H are explained in the text.)

agram of the chosen reflector.

The computer calculates estimated light intensities, including the minimum, maximum, and average light intensities. As shown in Figure 10.5, these values are:

Minimum light intensity	-	5,980 lux
Maximum light intensity	-	6,821 lux
Average light intensity	-	6,423 lux

Based on this data, the uniformity of the installation is calculated as 93.1% (minimum/average, or E_{min}/E_{av}), or 87.7% (minimum/maximum or E_{min}/E_{max}). The other parameters required for the calculation of the design shown in Figure 10.5 are:

Type of reflector	-	Deep
Lamp wattage	-	600 W
Lumen output	-	87,000 lm
Mounting height	-	2.50 m
Entire mounting grid	-	8 x 8 luminaires
Rectangular mounting pattern	-	4.50 x 2.67 m (13.6 m^2)

To determine the average light intensity and uniformity for the entire mounting grid, a representative area or calculation field (Figure 10.5) is selected underneath four centrally located luminaires, whereby the influence of the surrounding luminaires is taken into account. In the calculation field, 121 (11 by 11) points were calculated. The distances between the calculation points were thus 0.45 m and 0.267 m.

The light intensity across the calculation field is shown in Figure 10.5 through different degrees of shading (the

***Figure 10.4.* The predicted effect of light pattern overlap on plant growth.**

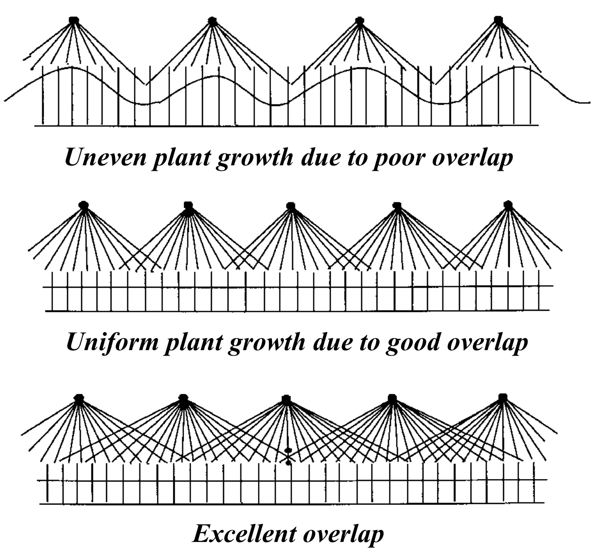
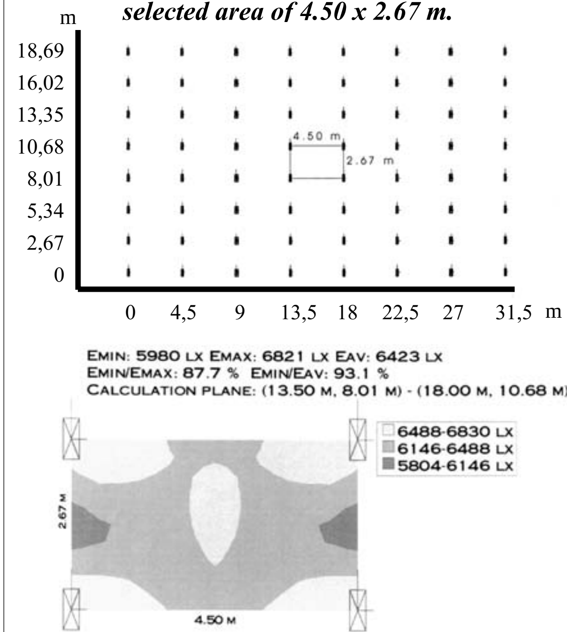


***Figure 10.5.* Light intensity and distribution for a selected area of 4.50 x 2.67 m.**



darker the shading, the less light). The highest light intensity is received at those areas directly underneath the luminaires and in the center of the calculation field where the light patterns of the four luminaires overlap.

Uniform plant growth

Uniform plant growth can only be obtained with uniform light distribution, because plant growth is determined by the amount of light. Uniform light distribution not only promotes production of fruits, leaves, or flowers, but also promotes overall plant quality. The percentage of first quality product (based on stem thickness, bud size, stem weight, color, etc.) increases. It is not unusual for crop yield to increase with at least 10% due to uniform light distribution.

Comparison of two greenhouse operations

Let's assume that the supplemental lighting installation in a particular greenhouse operation has a very poor light uniformity (E_{min}/E_{max} = 50%), while another greenhouse operation has an excellent uniformity (E_{min}/E_{max} = 90%). Furthermore, suppose the greenhouse operation with the poor light uniformity is able to produce a crop worth $36 per square meter per year during the dark period of the year. Thus, the greenhouse operation with the excellent light uniformity is able to realize an additional yield of 10%, or $3.60 per square meter per year.
Assuming a greenhouse size of 1 hectare (10,000 m^2 or 2.5 acres), then each percent increase in light uniformity results in an additional yield of $36,000/(90-50) = $900 per hectare per year.

Comparing the effect of different reflectors

Figure 10.6 clearly shows the importance of choosing the right reflector for a particular light distribution. The two calculation fields were evaluated using the HS2000 Deep 600 W and HS2000 Midi 600 W luminaires. The mounting height was 2.30 m. The luminaires equipped with the Midi reflector clearly provide the best uniformity.

Figure 10.7. ***Installation of luminaires.***
top: ***C-profile;*** *bottom:* ***trusses.***

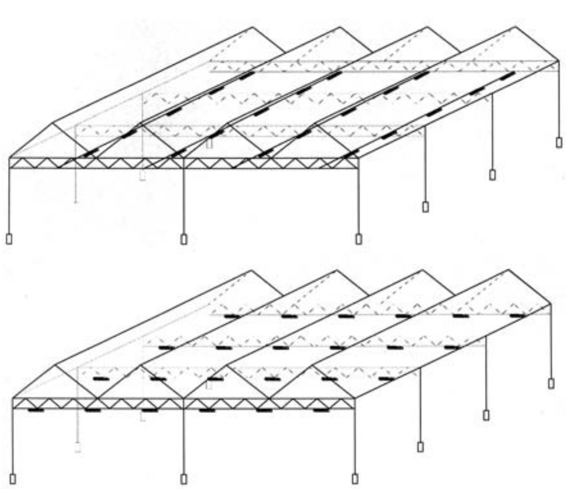


Figure 10.6. ***Comparing the effect of different reflectors on light distribution and uniformity.***

top - ***HS2000 Deep 600 W reflector***
bottom - ***HS2000 Midi 600 W reflector***

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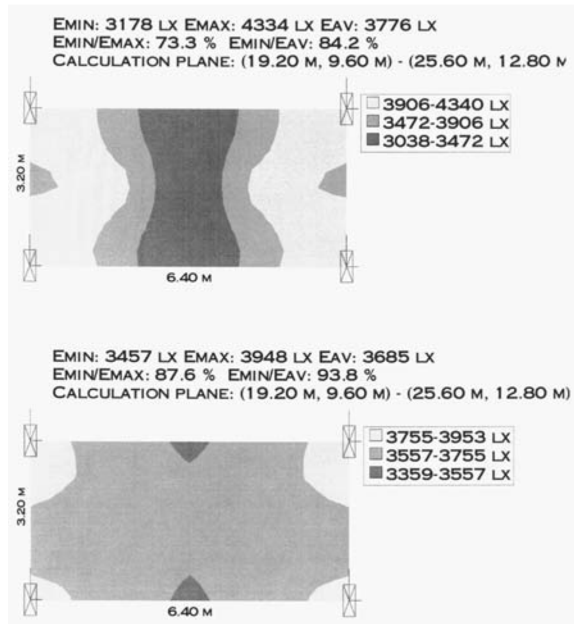


10.2.3 Installation

Usually, the luminaires are installed in one of two ways:

1. Parallel with the direction of the gutter, for example mounted on a C-profile that is attached to the trusses (Figure 10.7, top);
2. Across the direction of the gutters (*e.g.* at the bottom of the trusses as in Figure 10.7 (bottom).

1. *C-profile*

Suppose a supplemental lighting system is installed in a greenhouse with 8 m wide bays with two 4 m wide roof segments and a distance of 4.5 m between the posts. And suppose the desired lighting intensity is approximately 6,500 lux. In this situation, a mounting pattern of 4.0 x 3.0 m is feasible installing 1 row of 600 W fixtures in the middle of each 4 m roof segment (resulting in one luminaire for each 12 m^2 of floor area.
When using a C-profile, the desired lighting intensity can usually be achieved with a high uniformity because it is easy to add an extra luminaire within a row.

2. *Trusses*

Suppose a supplemental lighting system is installed in a greenhouse with 8 m wide bays with two 4 m wide roof segments and a distance of 4.5 m between the posts. At a desired light intensity of approximately 6,500 lux, a mounting pattern of 4.50 x 2.67 m is fea-

Figure 10.8. ***Without adding more luminaires along the outside greenhouse wall.***

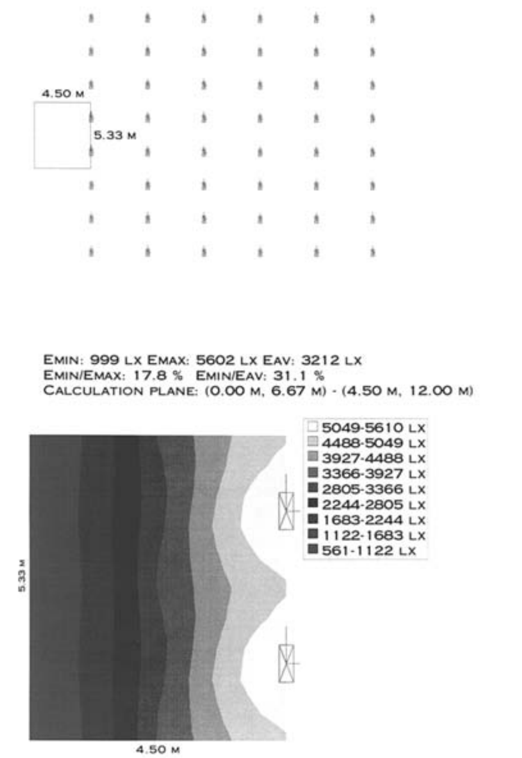
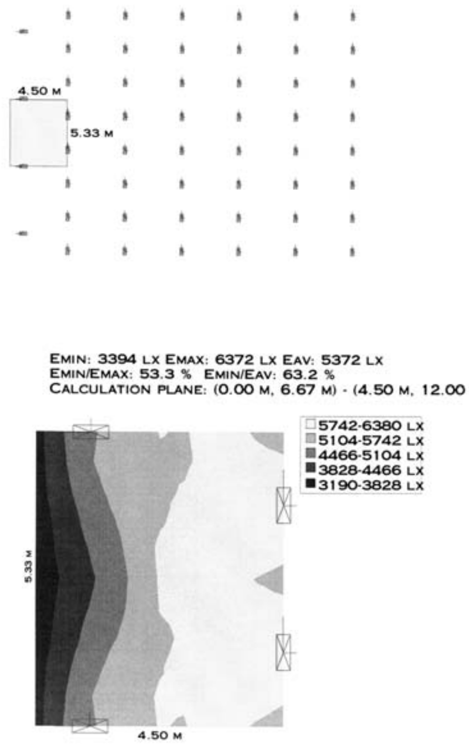


Figure 10.9. ***With adding more luminaires along the outside greenhouse wall, (Outside wall compensation).***



sible installing three 600 watt luminaires at the bottom of the trusses resulting in one luminaire for each 12 m^2 of floor area (Figure 10.7). The advantage is that no C-profile is needed and that the shade of the luminaire coincides with the shade of the trusses.
A drawback is that adding extra luminaires can interfer with the location of the greenhouse posts.

10.2.4 Edge effects and obstacles

Near outside walls and walkways, the light intensities are lower than towards the middle of the greenhouse. This is because the light comes from one general direction and not from all directions. The reduction in light intensity near the outside walls of a greenhouse is clearly shown in Figure 10.8 (the luminaires are mounted at the bottom of the trusses). The last fixtures in each row in this example are mounted at a distance of 4.5 m from the outside wall. The reduction in light intensity can be somewhat reduced by adding more luminaires (and rotating them 90 degrees) as shown in Figure 10.9.

Adding extra luminaires near the outside walls
Extra luminaires can be added near the outside walls (Figure 10.9). In addition, installing reflecting wall curtains can considerably reduce the edge effect. It is clear that for uniform plant production throughout the entire greenhouse growing area, the reduction in light intensity should be reduced as much as possible

Obstacles producing shadow bands
Every obstacle in the path of the light from a reflector can adversely affect uniformity and light intensity. The heating pipe shown in Figure 10.10 creates some unwanted shade.

No obstacles in the light track
Once the angle of the radiation produced by a reflector is known, it is possible to determine at what location the luminaires should be mounted to prevent unwanted shadow bands. The heating pipe shown in Figure 10.11, is positioned high enough as not to create any shade and, thus, without influencing the light intensity and uniformity.

Figure 10.10. ***Obstacles producing shadow bands.***

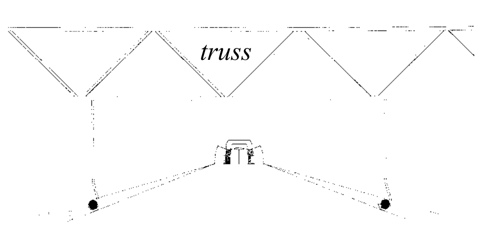
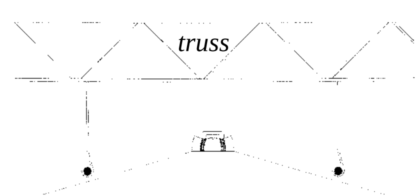


Figure 10.11. ***Without obstacles producing shadow bands.***



11 Electrical Installation

A properly installed supplemental lighting system starts with the installation of the luminaires in compliance with local and/or national electric code regulations.

11.1 Regulations

Designing and installing a supplemental lighting system is work for a specialist. For this reason, *Hortilux Schréder B.V. and P.L. Light Systems, Inc.* only sell their products through certified electricians. Certified electricians have the knowledge and expertise to properly install a supplemental lighting system. The electrical installation should comply with all local electrical code regulations. It is recommended to contact the local electric utility company for any specific requirements for the installation of supplemental lighting systems. In addition to electric code requirements, you may have to comply with specific labor laws (especially with regard to safety issues) during the installation of supplemental lighting systems. Your certified electrician will, in most cases, be responsible for compliance with electrical code regulations.

11.2 Wiring

All wiring should be sized as to limit voltage drop, so that the occurring voltage loss remains within certain boundaries. In The Netherlands, a voltage drop of less than 2% is usually recommended by certified installation companies. Such a recommendation provides that the voltage to a luminaire towards the end of the supply line to be within a 2% range of the voltage to a luminaire at the start of a supply line. A further reduction of the voltage drop would not warrant the extra investment for an improved wiring installation.
The voltage supplied to each luminaire should be within the nominal voltage range. When the voltage drop is more than 2%, more electric power will be lost as heat generated in the wiring. This power loss starts as soon as the lamps are turned 'on'. In addition, the total load should be equally distributed over the different phases. Finally, the ground wires should have the same diameter as the phase wires.

11.3 Voltage, current and frequency

The amount and shape (wave form) of the voltage are very important for optimal operation of high-intensity discharge lamps. In addition, the frequency of the electric grid plays a key role. A number of these characteristics will be discussed below.

11.3.1 High line voltage

Once a gas discharge lamp is ignited, it needs some time before it reaches maximum light output. The warming-up period for high-pressure mercury lamps is about 3 minutes, and for high-pressure sodium lamps it is 10 to 15 minutes. Immediately after turning on the line voltage, the light generated by a high-pressure sodium lamp is whiter in color. After some time the color gradually changes to yellow-orange. The white color is created by the high initial current through the filament of the lamp. As the lamp reaches the final operating temperature, the current gradually drops to its rated level.
The ballast regulates the balance between lamp current and lamp voltage. When the nominal voltage, for which the luminaire is designed, is supplied, the lamp operates according to the technical specifications. With higher line voltages, the ballast sends a higher current through the lamp. Supplying a permanently higher line voltage may have a negative effect on the lamp life and light output. Supplying a higher line voltage results a higher light output. In the European system, using a line voltage of 240 V results in a 20% higher light output compared to a line voltage of 230 V (Figure 11.1). The life span of the lamp, however, is reduced by 50%.

11.3.2 Low line voltage

In The Netherlands, the line voltage fluctuates between -6% and +10%. The electric utilities in The Netherlands try as much as possible to provide a constant voltage of 230 V. In a particular installation, the voltage drop may be as high as 10 V below the nominal value. This can occur when the distance between the supply line and the last luminaire is very large and/or when inadequate wiring has been used. As a result, a significant voltage drop may occur. As discussed earlier, a voltage drop of about 2% is considered to be acceptable. To save costs (by using thinner wires), sometimes a voltage of 210 V is supplied to the luminaires at the end of the wiring in a lighting system. This has no negative effect on the life span of lamps or luminaires. However, as an example, the light output at 220 V is reduced to approximately 85% compared to the light output at 230 V. Supplying voltages below 200 V could prevent the lamps from igniting.

11.3.3 Voltage distortions

In addition to harmonic currents (Section 8a.2.5), other negative effects may occur in large-scale installations with high intensity discharge lamps. Due to the large load, the voltage waveform may lose its sinusoidal shape. This usually corresponds with a significant increase in the top-top value of the waveform. As a result, the lamp tends to go out sooner (when the sinusoidal wave passes through zero). Therefore, the lamp does not reach its normal operating temperature and it produces considerably less light. If these voltage distortions are more than 3%, the loss in light output can be clearly observed.

11.3.4 Frequency fluctuations

Ballasts are sensitive to frequency fluctuations. In a co-generation installation, the frequency may fluctuate due to a number of reasons. For example, the frequency may drop when a large number of luminaires is turned on simultaneously. For a short period of time, the generator can not handle the sudden increase in demand and the frequency drops slightly from *e.g.* 50 hertz (Hz) to 49 Hz. As a result, the inductive resistance of the ballast declines. Due to the lower impedance, a higher current passes through the lamps straining the generator even more. The frequency drops further, resulting in even more current passing through the lamps. A downward spiral develops resulting in potential damage to the lamps. For example, instead of the normal value of 400 W a lamp now uses 600 W at 30 V. To prevent this situation from occurring, a regulator stabilizing the frequency between 48 and 52 Hz is connected to an off-switch as a safety device. The switch is activated when the frequency drops below 47.5 Hz and this prevents damage to the lamps and ballasts. At frequency above 50 Hz, the ballast resistance increases. As a result, less current passes through the lamp and the light output drops.

11.4 Practical aspects

11.4.1 Maintenance

Like any other piece of equipment, a lighting installation requires maintenance. In The Netherlands, proper maintenance of the lighting installation is required by law. Using a logbook is an effective tool to record all necessary information and repairs. When a lamp fails several times in the same luminaire, there may be other problems that need to be investigated. The data entered in the logbook can provide valuable information about the overall operation of a supplemental lighting installation.

11.4.2 Lamp replacement

When a lamp should be replaced is determined by its useful or economic life. Although the lamp may appear to operate normally (Section 7.3), the light output may have decreased significantly. As a rule of thumb for HPS lamps, the light output declines approximately 10% for every 10,000 burning hours (Figure 11.2). At this point, the economic life of the lamp has been reached and the lamp should be replaced. A calculation example will show this point further.
In The Netherlands, a greenhouse for rose production using a supplemental lighting installation achieves an average income during the winter of approximately $36 per square meter. As stated earlier, another rule of thumb states that 1% extra light results in 1% extra growth. If growth and yield are

Figure 11.1. ***Effect of line voltage on SON-T lamps (HPS)****. Source: Philips, 2000.*

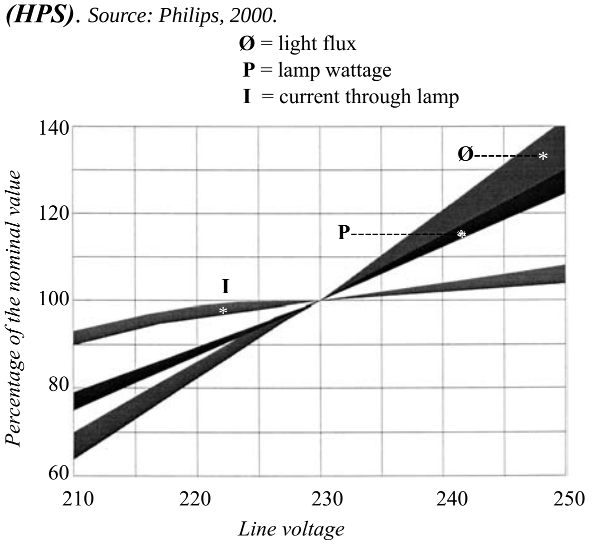
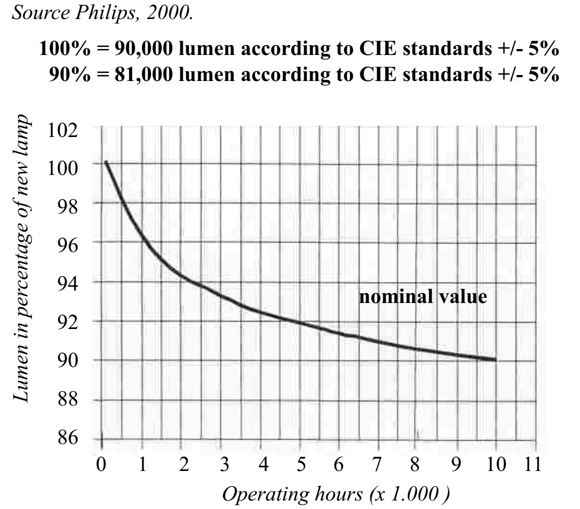


Figure 11.2. ***Relationship between operating hours and light output (lm) for a SON-T Plus 600 W lamp.*** *Source Philips, 2000.*



related in this way (Section 11.4.3), 10% light loss corresponds with a loss in income of $3.6 per square meter. At the same time, the energy consumption is not reduced, as is clear in the following example.

Suppose a greenhouse supplemental lighting system is operated for 4,500 hours per year at a luminaire density of one luminaire per 12 m^2 of floor area (600 watt HPS lamps). The lamps are used until they have accumulated a total of 14,000 burning hours. The decline in light output is 10%, on average, over the last 4,500 hours. The cost for the unused electricity per square meter is (note that this amount of electricity is converted into heat):

(10% x 0.6 kW x 4,500 h x $0.05 per kWh)/12 m^2 = $1.13/$m^2$

The calculation shows that $1.13 per square meter is paid for electricity that is not used for the generation of light. In addition, the number of failed lamps strongly increases after 10,000 burning hours. Lamp manufacturers usually state that a HPS lamp has a maximum life of 24,000 burning hours. However, they do not state clearly that half of all the lamps may then be defective (average life span, Section 7.3). This is not acceptable in modern greenhouse operations. From a practical point of view, a 1% failure rate per 1,000 burning hours can be expected. Initially when a new system is started up, this failure rate may be slightly higher. *Hortilux Schréder B.V. and P.L. Light Systems* implemented a lamp warranty plan, providing free lamp replacements if lamp failure occurs within 10,000 burning hours. The plan can be extended for up to three lighting seasons. Lamps are replaced for free, except when failures are due to glass breakage, water damage, or excess voltage (please consult the general terms and conditions).

11.4.3 Light output per luminaire

The light output per luminaire is very important because every percent of light counts. As an example, lighting experiments were conducted with the rose cultivar 'First Red', using 600 watt HPS luminaires and about 4,000 burning hours per year (source: PBG). During the darker winter months, an increase in light intensity from either 4,000 or 4,200 lux resulted in a production increase from 1,990 and 2,090 gram/m^2, respectively.

Thus, the 200 lux increase in light intensity resulted in a 100 gram/m^2 production increase. Or, expressed in percentages,

5% more light resulted in 5% more production.

During the darker winter months, this rule of thumb is valid for many crops. In addition to production increases, plant quality is usually improved as well. As a result, the quality of the supplemental lighting system can have a significant impact on the economic return of a greenhouse operation. A carefully designed supplemental lighting system is very important before you decide to invest in such a system. *Hortilux Schréder B.V. and P.L. Light Systems* provide the knowledge, expertise, and products to successfully guide you through the decision process.

Calculation of the light output of an installation

Table 11.1 shows how the light output of a supplemental lighting installation can be estimated. A large number of parameters that have a significant impact on the final light intensity provided to the crop have to be taken into account. First, there are variations in the light output from individual lamps. Second, the life expectancy of a lamp has an important effect on the light output. Assuming a lamp life of 10,000 hours, the average light output is 95% of the maximum light output. Furthermore, the light efficiency of a reflector ranges between 75 and 90% (in Table 11.1 86% because of dirt). The type of reflector and the mounting height are also important factors determining the light output. Taking all these parameters into account, the light output per luminaire and ultimately the light intensity per unit of greenhouse area can be estimated, (preferably expressed in µmol m^{-2} s^{-1} and carefully checked with a PAR meter after installation).

***Table 11.1.* Calculation of the light output from a 600 W HPS lighting system.**
Source: Van Rijssel, 1999, edited.

Lumen output *(new)*	87,000 *(lumen)*	1,060 *(µmol s^{-1})*
Average light output	95%	95%
Reflector efficiency	86%	86%
Lumen output per luminaire	71,079 *(lumen)*	866 *(µmol s^{-1})*
Greenhouse area per lamp	15 m^2	15 m^2
Expected intensity	**4,739** *(lumen m^{-2})*	**57.7** *(µmol m^{-2} s^{-1})*

Appendix 1. Hourly solar radiation per month for Vlissingen, 51°27'N.L., The Netherlands, in W m^{-2}.

These values are frequently used as set points for operating shade curtains and supplemental lighting systems. Table 5.4, where W m^{-2} has been converted into µmol m^{-2} s^{-1}, is based on the data presented in this table.
Source: Royal Dutch Meteorological Institute, Velds, 1992.

VLISSINGEN

hour	J	F	M	A	M	J	J	A	S	O	N	D
5	—	—	—	—	22	39	22	3	—	—	—	—
6	—	—	—	31	94	111	89	47	8	—	—	—
7	—	—	25	111	192	206	181	139	67	14	—	—
8	—	19	94	208	297	308	283	244	161	75	14	—
9	28	83	186	306	397	408	381	344	256	156	61	22
10	78	153	258	386	483	492	475	436	336	228	117	67
11	122	211	322	444	533	564	544	497	394	272	156	100
12	142	242	347	481	550	594	575	525	417	297	167	117
13	139	239	342	486	547	594	581	522	411	278	153	114
14	108	208	311	444	506	561	556	492	369	225	119	83
15	67	153	250	378	436	497	478	422	297	161	69	42
16	22	86	175	283	347	400	389	333	206	83	19	6
17	—	22	86	178	242	289	289	222	108	19	—	—
18	—	—	17	81	136	178	178	117	31	—	—	—
19	—	—	—	11	50	83	75	31	—	—	—	—
20	—	—	—	—	6	19	14	—	—	—	—	—

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